A New, Inexpensive Scanning Reflectometer and its Potential Use for Fruit Color Measurement

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ADDITIONAL INDEX WORDS. ripening, fruit color, field instrument, reflectometer, Colortron

SUMMARY. The use of a new, inexpensive scanning reflectometer, the Colortron, as a field and laboratory colorimeter is investigated. The results obtained from a series of color swatches and from a variety of fruit samples are compared with those obtained from other commercially available, but more expensive, colorimeters (Hunter and Minolta). The Colortron is shown to be very good for gathering and analyzing data. The results of all three instruments were extremely close when measuring color swatches, but the Colortron gave aberrant results with certain fruit having translucent skin and flesh. Despite this caveat, it still has considerable potential for the measurement of fruit color in the field and laboratory.

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We thank Karl J. Siebert for carrying out some of the statistical analyses, and for helpful discussions on this aspect of the paper. The cost of publishing this paper was defrayed in part by the payment of page charges. Under postal regulations, this paper therefore must be hereby marked advertisement solely to indicate this fact.

A new instrument, the Colortron desktop scanning spectrophotometer (Light Source, Larkspur, Calif.), has been introduced commercially. It is intended for color matching in the desktop publishing industry and, as such, has been designed as an inexpensive piece of equipment that plugs directly into a Macintosh computer. It rapidly records the reflectance spectrum of a color on a flat surface and then computes a range of standard tristimulus parameters commonly used in the publishing industry and in other color applications. A tungsten light source is used; the reflected color passes through a diffraction grating and the intensity is measured and stored. The spectrum is measured in 10-nm increments from 390 nm to 710 nm, and this is the base data from which other parameters are calculated by standard mathematical transformations.

This device can be used as a scientific tool for measuring the color produced (the analytical signal) in field assays for environmental contaminants (Reeves and Durst, 1995). The Macintosh system requirements are a 68020 processor or later, System 7.1 or later, 5 megabytes of disk storage space, and at least 2 megabytes of available RAM. A color monitor is preferable, but not required. This work was conducted with the Colortron attached to a desktop Macintosh with a color monitor, but some measurements were taken with the Colortron attached to a portable Powerbook with a monochrome screen. A large number of measurements could be taken with the portable computer and then transferred to a desktop machine later. Thus, the device can be used in either a laboratory or field setting.

Because the Colortron is a scanning rather than a tristimulus device, it can also provide useful data in other areas of scientific endeavor. Using fruit color as an example, spectral changes could be followed as the fruit ripened and changed color. This could give information not obtained by the older versions of the more commonly used tristimulus meters, which assess color based on the response of a limited number of specific color sensors. The latest versions of both these machines are capable of recording spectra, but are not available in many laboratories where color measurement is not the prime focus of research.

Color and its accurate measurement is of great importance in the horticultural industry (Francis, 1980; Gonnet, 1995), and so the Colortron was used to estimate the color of several different fruit, and the results obtained were compared with measurements on the same fruit taken with the other colorimeters commonly used in laboratories dealing with fruit color.

Materials and methods

COLOR ESTIMATION. A HunterLab D25-PC2 Colorimeter (Hunter Associate Laboratory, Inc., Reston, Va.) was used, following the manufacturer's instructions. The sensor was used in the inverted orientation so that the fruit could be placed on top, and a small aperture plate was used, giving a circular measurement area with a diameter of 25 mm (491 mm²). The light source was a halogen cycle lamp, and the colorimeter was attached to a Radio Shack TRS-80 computer using a locally written program (M. McLellan, personal communication).

The second standard colorimeter used was a Minolta Chroma Meter (CR-100) with an attached data processor (DP-100) (Minolta Corp., Ramsey, N.J.). This was a hand-held instrument with an 8-mm-diameter, circular measuring area (50 mm²). The light source was a pulsed xenon arc lamp with a double-beam feedback system for accuracy control. The instrument was set to take an average of three readings while the measuring head was held at one position on the fruit.

The Colortron was used as described earlier (Reeves and Durst, 1995). The light source was a small tungsten bulb, and the 3-mm square aperture (9 mm²) was placed over the area to be measured and a spectrum was recorded in about 6 seconds.

Data from the Hunter and Minolta instruments were manually entered into Microsoft Excel or CA-Cricket Graph III (Computer Associates, Islandia, N.Y.) for analysis and graphing purposes. It is possible to connect the Hunter and the Minolta colorimeters to a computer at extra cost, but this was not done here, and the connection would be to a DOS machine rather than a Macintosh. Data from the Colortron was exported directly as Tab Delimited Text to either Microsoft Excel or CA-Cricket

Table 1. Types of tristimulus data calculated by the Colortron. All the calculations are made by the computer from the spectral data obtained by the scan of the color. The values of any or all of the parameters shown below can be exported as tab-delimited text to spreadsheet, graphical, or statistical applications.

Definitions

CIE	Commission Internationale de l'Eclairage		
Lab	L (Lightness)	a (green-red)	b (blue-yellow)
XYZ	Three imaginary primaries defining all colors (rarely used)		
xyz	xy (chromaticity coordinates)	Y (Luminance)	
Luv	A more perceptually uniform color space than xyz		
HSB	Hue (angle around a defined color wheel), Saturation (similar to Munsell's chroma), and Brightness (Lightness).		

NTSC (National Television Standards Committee), PAL (Phase Alternation by Line) and Monitor (computer or television monitor) RGB (Red, Green, Blue) are designed for computer monitor measurements.

CIE Lab	L = 59.08	a = -0.05	b = 37.24
CIE XYZ	X = 26.56	Y = 27.11	Z = 11.55
CIE xyY	x = 0.4072	y = 0.4156	Y = 27.11
CIE Luv	L = 59.08	u = 20.12	v = 46.38
HSB	H = 42	S = 60	B = 58.43
NTSC RGB	R = 154	G = 142	B = 84
PAL RGB	R = 163	G = 138	B = 76
Monitor RGB	R = 149	G = 124	B = 60

Graph III and pasted into Statistica for further analysis.

All three instruments were used with "simulated daylight" used in the calculations.

EXPERIMENTAL MATERIALS. As a first step in comparing the Colortron with more established devices, color swatches were measured using the Colortron, Hunter, and Minolta instruments. It was decided to carry out the measurements recording CIE (Commission Internationale de l'Eclairage) $L^*a^*b^*$ values with simulated daylight as the reference light source, as all three machines could be set up to read and record these values. A series of 24 swatches was measured 5 times with each device, and the average and standard deviations were calculated in each case.

Further experiments were then carried out on 18 different fruit samples, which were obtained from a local supermarket, consisting of two each of apples, ripe tomatoes, bananas, oranges, mangos, peaches, nectarines, and red bell peppers and one each of green and yellow bell peppers. All fruit measurements were taken on the day of fruit purchase to reduce ripening effects. A circular area about 40 mm in diameter was marked on the surface, and all measurements were taken within this area.

A small number of samples of fruit with a wide variety of colors was used deliberately, as the objective of this paper was to introduce the reader

to a relatively new instrument. Obviously, individual scientists would prefer a more exhaustive analysis of the single fruit of interest to them, but this was not possible within the confines of a single paper. The instrument can be purchased by an individual with a 30-day money back guarantee for such studies.

Five measurements were taken in all cases and averaged, and the standard deviations were calculated using the spreadsheet function in Microsoft Excel.

USING THE COLORTRON. The Colortron aperture is placed over the area whose color is to be measured, and a spectrum is recorded in about 6 seconds. This measurement is saved in a file on the computer and can be named as required. The same file can contain a large number of readings, each named individually, and individual files can be renamed, copied, and transported from one file to another or from

one Macintosh to another. The "Spectrum" window displays the spectrum of the selected color, and the "Colorimeter" window displays any selected three of the eight parameters that the

Fig. 1. A typical reflectance spectrum obtained from the Colortron. A single scan was carried out, and the data were exported to a graphics program and plotted. The y axis of the graph shows the intensity of the reflected light, with 1.0 being total reflection. The tristimulus calculations made by the Colortron from this spectrum are shown in Table 1.

Fig. 2. Comparison of L^* values for 24 color swatches. Measurements were taken with all three colorimeters.

application calculates from the spectral data. The spectral data and/or any of the eight parameters can be selected and exported to any graphics or spreadsheet application for further analysis and the production of presentation graphics. Individual readings within a single file can be averaged by a simple "Drag and Drop" procedure, and the averaged spectrum and data are saved as another item in the file. These data-handling characteristics make the acquisition, manipulation, comparison, and archiving of data extremely simple and efficient. A sample of such exported tristimulus data is presented in Table 1, and a spectrum drawn of the wavelength data from which it was calculated is shown in Fig. 1.

The Colortron can also average the readings of a large area of fruit surface by dragging the aperture over the desired area. This function was not examined in detail, but has potential in the estimation and quantitation of the

color development in fruit that do not ripen evenly.

Results and discussion

COMPARISON USING COLOR SWATCHES. Color swatches were measured using the Colortron, Hunter, and Minolta colorimeters.

The Hunter gave the smallest standard deviation between measurements (0.05), the Colortron

the largest (0.47), and the Minolta intermediate (0.14). All these levels of variation are acceptable, and it seems likely that they are related to the sample size, that is, the total area of the swatch surface used for measurement. As noted above, the Hunter used a circle 25 mm in diameter, the Minolta a circle of 9 mm diameter, and the Colortron a 3-mm square. This gives respective measurement areas of 491, 50, and 9 mm².

Regression analysis was then carried out on the average CIE $L^*a^*b^*$ results for the swatches, and equations were derived for the resultant correlations. The results for one of the three parameters (L^* values) are plotted in Fig. 2, and the full results are presented in Table 2. These data clearly show that the three devices are measuring the color of the swatches in a very similar manner. The adjusted r^2 values (the most conservative correlation coefficient) are all >0.92 ($n = 22$), and the slopes range from 0.92 to 1.23. The CIE L^* value correlations, in terms of r^2 , slope, intercept, and standard error, are the closest of the three parameters among the three instruments, with the CIE a^* values

next, and the greatest variation being shown in the CIE b^* values. However, in all cases, the agreement is very good. This result is not unexpected, as color swatches are flat and have even color distribution over the entire surface, as opposed to the case of fruit surfaces, and studies in this area are detailed next.

COMPARISON USING FRUIT. Measurements were made on 18 different fruit samples with each instrument, and 5 measurements were taken from the same area of each fruit and averaged. The average standard deviations found were in the same order as with the color swatches. The Hunter gave a result of 0.21, the Minolta 0.41, and the Colortron 1.78. As might be expected, these variations are larger (by a factor of about 4) than was the case with the swatches, due to the much greater variability of the fruit surface.

Table 3 shows the statistical analysis of the fruit data. This presents a very different picture from the data obtained from the swatches (Table 2). Comparing the Hunter and the Minolta, the CIE L^* and a^* values are in very good agreement. The CIE b^* values are very closely correlated, but the slope of the line is 1.67, indicating that the value of b^* as measured by the Minolta changes nearly twice as much as that of the Hunter as the color changes from blue to yellow. We have no adequate explanation for this at the moment, and it is possibly a characteristic of one of these instruments.

When the Hunter and the Colortron are compared, there is surprisingly poor correlation, especially in the case of the L^* values, and only slightly better correlation between the Colortron and the Minolta. When the data were plotted it became obvious that there were two apparently independent groups of results for the Color-

Table 2. Statistical analysis of CIE $L^*a^*b^*$ values of color swatches measured using three different instruments.

Parameter	Dependent variable	Independent variable	Adjusted r^2	Slope	Intercept	SE of estimate
CIE L^*	Colortron L^*	Minolta L^*	0.94	0.96	0.47	3.90
CIE L^*	Colortron L^*	Hunter L^*	0.98	0.94	8.65	2.40
CIE L^*	Minolta L^*	Hunter L^*	0.99	0.95	9.6	1.92
CIE a^*	Colortron a^*	Minolta a^*	0.93	1.13	0.86	8.41
CIE a^*	Colortron a^*	Hunter a^*	0.98	1.13	2.80	4.65
CIE a^*	Minolta a^*	Hunter a^*	0.95	0.96	1.5	5.89
CIE b^*	Colortron b^*	Minolta b^*	0.98	0.92	2.75	4.64
CIE b^*	Colortron b^*	Hunter b^*	0.95	1.15	9.76	8.17
CIE b^*	Minolta b^*	Hunter b^*	0.93	1.23	7.66	10.34

Table 3. Statistical analysis of CIE L*a*b* values of fruit measured using three different instruments.

Parameter	Dependent variable	Independent variable	Adjusted r^2	Slope	Intercept	SE of estimate
CIE L*	Colortron L*	Minolta L*	0.86	0.85	6.70	5.17
CIE L*	Colortron L*	Hunter L*	0.75	0.79	2.83	6.88
CIE L*	Minolta L*	Hunter L*	0.96	0.97	2.49	3.12
CIE a*	Colortron a*	Minolta a*	0.93	1.78	2.53	2.75
CIE a*	Colortron a*	Hunter a*	0.83	1.77	-0.68	4.25
CIE a*	Minolta a*	Hunter a*	0.93	1.00	-4.24	3.29
CIE b*	Colortron b*	Minolta b*	0.94	0.64	0.64	2.86
CIE b*	Colortron b*	Hunter b*	0.86	1.08	1.08	4.20
CIE b*	Minolta b*	Hunter b*	0.90	1.67	1.67	5.60

tron. This is most clearly seen in the case of the L* values (Fig. 3a). There is a small group of 5 low L* values that appear to be separate from the remaining 13 values. Upon inspection of the original data, these turned out to be values recorded for the tomatoes and the bell peppers. When measurements with the Colortron were being taken on these fruit it, was noticed that they were translucent, and much of the light seemed to pass straight through them. This was not true of the other fruit tested. If it is indeed the case that these fruit do not fully reflect the light, then such variations as seen in the table would occur and would be expected most strongly in the L* value, as this is dependent on the intensity of the color. The a* and b* values should be less affected, as they are parameters of the color rather than the intensity. If these 5 low measurements are removed and the statistical calculations are repeated on the remaining 13 values, there is an improvement in correlation of all 3 parameters, with the most dramatic improvement being seen in the L* value (Table 4). It is interesting to note that the fruit measurements that were much lower with the Colortron than with the Hunter were also slightly lower in the case of the Minolta (Fig. 3b). This suggests that this phe-

nomenon also occurs slightly with the Minolta and explains why the correlations between the Colortron and the Minolta are closer than might be expected (Table 3).

To demonstrate that transparency of the fruit skin and flesh was the cause of this problem, an apple sample and a tomato sample were compared. An area of the whole fruit was measured using the Colortron, and then that area of skin was removed from the fruit with a scalpel, giving a piece of peel about 1 to 2 mm thick. This skin alone was then remeasured, with either black paper, white paper, or aluminum foil as a backing. The resultant spectra are shown in Fig. 4. The apple skin is almost totally opaque; consequently, there is a very small increase in reflectance maximum with aluminum foil as the backing and a small decrease with the black paper (Fig. 4a). The changes in the L*a*b* values resulting from this are very small (Table 5). In the case of the tomato, the results are much more dramatic, with major changes in the reflectance maxima, along with shifts in the proportions of different areas of the spectrum (Fig.

4b). These changes are reflected in correspondingly large shifts in the L*a*b* values (Table 5).

The differences between the three instruments in measuring these fruit surfaces is presumably related to the geometry of the light source and the light collectors. In the case of the Colortron, the source is very close to the fruit surface, and a high degree of reflection is required for accurate measurement. In the Hunter and Minolta, the light source is much farther away. The overall geometry is very different, due to the fact that the Colortron has been specifically designed for measuring solid color in the desktop publishing industry, whereas the others were designed as laboratory instruments.

HUE ANGLE. It is not the purpose of this paper to comment on the appropriateness or otherwise of hue angle measurements (Little, 1975; McGuire et al., 1992; McLellan et al., 1995) for the analysis of fruit color. Also, as it is a calculated rather than a measured parameter, changes in the hue angle vary exactly as do the parameters from which it is calculated. However, the hue angle can be calculated from the

Fig. 3. Comparison of fruit L* values from all three colorimeters. (A) Colortron and Hunter; □ Colortron L* high, ◇ Colortron L* low. (B) Minolta and Hunter; □ Minolta L* high, ◇ Minolta L* low.

Table 4. Statistical analysis of CIE L*a*b* values of fruit measured by the Colortron and Hunter Colorimeters. For each of the three parameters, the "all" value is as in Table 3. The "selected" value is that one obtained when the translucent fruit measurements are removed from the calculations (see text).

Parameter	Dependent variable	Independent variable	Adjusted r^2	Slope	Intercept	SE of estimate
CIE L*-All	Colortron L*	Hunter L*	0.75	0.79	2.83	6.88
L*-Selected	Colortron L*	Hunter L*	0.98	0.76	7.98	1.75
CIE a*-All	Colortron a*	Hunter a*	0.83	1.77	-0.68	4.25
a*-Selected	Colortron a*	Hunter a*	0.87	0.84	0.07	3.95
CIE b*-All	Colortron b*	Hunter b*	0.86	1.08	1.08	4.20
b*-Selected	Colortron b*	Hunter b*	0.90	1.15	0.73	4.02

CIE a*b* results produced by the Colortron. Furthermore, one of the sets of tristimulus data calculated from the spectrum is HSB [Hue, Saturation, Brightness (Lightness)]. The hue angle referred to here has red as 0° (or 360°) and intermediate angles on the color wheel expressed as degrees. This is similar to the calculations made by McLellan et al. (1995) to produce hue angles over this range. Hue angles can be calculated from the CIE a*b* values or read directly from the colorimeter tool in the Colortron application. These do not give the same values, but they correlate exactly as they are both calculated from the same spectral data.

Conclusions

The Colortron is a fast and inexpensive device for measuring color, with excellent data handling capabilities as it is connected directly to a Macintosh Computer.

It has considerable potential as a field instrument for measuring the color of certain fruits and vegetables. A Mark II instrument has been released since the data in this paper were collected, and this instrument reportedly has better power management capabilities,

making it more useful as a field and laboratory instrument. This instrument gives the same results, but can record more spectra before recharging is required (Mathai and Durst, personal communication).

There are certain fruit surfaces that do not reflect light well enough for the Colortron to be used in situ. The examples measured in this report are bell peppers and tomatoes, but there are almost certainly others that were not used in this study. This obviously is a disadvantage, and the fruit surface transparency needs to be characterized before the Colortron can be used with confidence.

Spectral data can be obtained reliably on those fruit that are suitable for measurement using the Colortron, allowing changes in individual colored components to be monitored at the same time. This has considerable potential for ripening and senescence studies. The newer versions of the Minolta and Hunter instruments can also carry out this function, although those used in this work could not. The averaging function of the Colortron is, however, unique, and deserves further examination for such studies.

Cost. The Colortron can be purchased for less than \$1200. However, it cannot be used as a stand-alone instrument, it requires a computer. A basic Macintosh can be purchased for less than \$2000, giving a total price of \$3000 for a laboratory that does not have a Macintosh available. It should be pointed out that this computer does not have to be dedicated to the Colortron, but can be used for any other purpose as required.

The basic cost of the stand-alone Minolta CR-200 is \$5500 and that of the HunterLab Miniscan XE is \$7400. While these can carry out all the required analyses, further data manipulation and storage are very restricted. The addition of a suitable computer, cables, and software would increase the price of these instruments by about \$2500, increasing the difference be-

Fig. 4. Spectra of apple and tomato skins obtained with the Colortron. A portion of the skin was measured on the intact fruit and then that portion was excised. It was remeasured when layered on black paper, white paper, or aluminium foil. (A) Apple. (B) Tomato.

Table 5. Colortron measurements of L*, a*, and b* on apples and tomatoes. Measurements were made on apples and tomatoes. First an area of the fruit was measured (fruit), and then that area of skin was removed from the fruit and remeasured when placed on white paper, black paper, or aluminium foil as a backing.

Fruit type	Fruit	White	Black	Silver
Apple				
L*	19.73	20.65	19.27	21.43
a*	29.64	27.52	27.42	27.73
b*	10.23	9.01	9.12	9.57
Tomato				
L*	24.70	33.50	17.40	40.34
a*	7.32	14.32	0.85	15.72
b*	21.99	33.49	17.33	37.84

tween them and the Colortron. If a suitable computer is already available, there would still be an investment of about \$500 for the cable and software, both of which are included in the price of the Colortron.

Overall, under the right circumstances, we believe that the Colortron is a viable and less expensive alternative to the other instruments currently available.

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Impact of Adjuvants on Pecan Foliage

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ADDITIONAL INDEX WORDS. surfactants, stickers, spreaders, photosynthesis, stomatal conductance

SUMMARY. Of 18 commonly used adjuvants evaluated on pecan [*Carya illinoensis* (Wangenh.) K. Koch], a few exhibited potential for substantially suppressing net photosynthesis (*A*) and the conductance of foliage to water vapor (*g_w*) when used within their recommended concentration range; however, most provided no evidence of adversely influencing *A* or *g_w*. Suppression of gas exchange by certain adjuvants persisted at least 14 days after a single application. The recently developed organosilicone-based surfactants generally exhibited the greatest potential for suppression. These data indicate that orchard managers should consider the potential adverse influence of certain adjuvants when developing orchard management strategies.

Profitable commercial cultivation of pecan in many portions of the world generally necessitates multiple foliar applications of a wide variety of pesticides during the growing season. Adjuvant-type agents are often added to these agrichemicals to enhance efficacy and/or reduce costs (Anonymous, 1996) by improving coverage and penetration/adhesion, facilitating mixing, enhancing the compatibility of spray mixtures, or ensuring pesticide stability (Harvey, 1992).

While they confer major benefits by functioning as either wetting/

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Chemical names are necessary to report factually on available data; however, the USDA neither guarantees nor warrants the standard of the product, and the use of the name by USDA implies no approval or disapproval of the product to the exclusion of others that may also be suitable. The cost of publishing this paper was defrayed in part by the payment of page charges. Under postal regulations, this paper therefore must be hereby marked advertisement solely to indicate this fact.