https://doi.org/10.2352/ISSN.2470-1173.2020.12.FAIS-173

Assessing the Use of Smartphones to Determine Crop Ripeness

Katherine Carpenter and Susan Farnand
Munsell Color Science Laboratory, Rochester Institute of Technology, Rochester, NY, USA

Abstract

Farmers do not typically have ready access to sophisticated color measurement equipment. The idea that farmers could use their smartphones to determine when and if crops are ready for harvest was the driving force behind this project. If famers could use their smartphones to image their crops, in this case tomatoes, to determine their ripeness and readiness for harvest their farming practices could be simplified. Five smartphone devices were used to image tomatoes at different stages of ripeness. A relationship was found to exist between the hue angles taken from the smartphone images and as measured by a spectroradiometer. Additionally, a tomato color checker was created using the spectroradiometer measurements. It is intended to be made of a material that makes it easy to transport into the field. The chart is intended for use in camera calibration for future imaging. Different cloth materials were tested, with the eventual choice being a canvas material with black felt backing. Other possibilities are being investigated. The results from the smartphones and the charts will be used in further research on the application of color science in agriculture. Other possible future applications include monitoring progress relative to irrigation and fertilization programs and detection of pests and disease.

Introduction

Smartphones are have become prevalent in cultures across the globe, including poor and underserved countries [1]. While farmers in such countries may not have access to laboratory-grade equipment or fleets of drones, they are likely to have a cell phone. Additionally, smartphone cameras would be much easier and more portable for use in field measurements than current lab-based spectrophotometers or spectroradiometers. If enough color information can be obtained from smartphone imaging, it could mean that data collection could be performed without having to transport expensive, cumbersome equipment. The current project focused on the potential use of smartphone cameras to determine the ripeness of tomatoes.

The purpose of the project is to determine if the relationship between color in smartphones and color measured by spectroradiometers is well-defined enough to get meaningful data from smartphone-captured images. Five smartphone or smartphone-level devices were used to image tomatoes at different stages of ripeness. The color information from the images was compared to measurements from a PR-655 spectroradiometer. The data collected was used in creation of a tomato color chart for camera calibration. Camera calibration is important especially for smartphone cameras because smartphones have different color correction algorithms and white balance. Generally, no two different phone models will capture exactly the same colors. Even phones of the same model were found to capture color differently [2].

The color checker was intended to be made of a material that makes it easy to transport into the field without taking up much space. Three charts were printed on different cloth materials and analyzed for their color correctness and other factors that could affect its usability, such as transparency. The three materials were all found to require backings of some kind. Five types of backings were tested to determine the most effective approach.

It was found that the relation of hue angles of tomatoes from the smartphone images, h_{phone}, were related exponentially to the measured hue angles of the tomatoes, h_{meas}. This relationship suggests that it is possible to use smartphones to gather relevant color information.

The use of inexpensive cameras and targets with ground-based autonomous vehicles could also open the world of in-situ measurement without the added complications of drone flight and regulations. It potentially increases the efficacy of crop monitoring relative to drone-based monitoring because it allows for imaging underneath the plant foliage. Such imaging also opens possibilities of applications such as monitoring progress of precision irrigation and fertilizer application as well as disease and pest detection. Additionally, similar technology could be used post-harvest for food sorting.

Background

Color has long been used by consumers as a gauge of quality of produce. It is the first thing observed by consumers when shopping. Consumers' perception of color can also affect their perceptions of other qualities, such as the sweetness of fruits [3]. The red color indicating ripeness in tomatoes is directly related to lycopene content within the tomato [4]. Lycopene is a carotenoid; carotenoids are pigments found within foods that contribute antioxidant qualities to the foods, of which lycopene is the most efficient [5]. The concentration of carotenoids in tomatoes increases between ten and fourteen times over the growth and maturation of the tomatoes [6]. The chlorophyll that creates the green color breaks down as the carotenoids build up [5]. As the concentration of lycopene increases, the tomato becomes redder. The color of raw tomatoes even determines the resulting colors of processed tomato products, such as paste and ketchup [7]. As such, the proper color at harvest can be paramount to farmers' success.

A wide array of environmental factors can affect the development of color in tomatoes, both during growth and post-harvest, including natural light [8], ripening on or off the vine [9,10], temperature during growth [4], and biological variation [11]. This makes it essential that farmers monitor their crops at every stage of development. Some farmers have turned to drone imaging to survey the state of their fields [12_14]. However, drones can be expensive and are heavily regulated by the Federal Aviation Administration in the United States [15]. Farmers in more rural or impoverished countries may not have access to drones at all. Tomatoes can still be a staple of agriculture in such places without drone technology [16-18]. With the pervasion of smartphones through all cultures around the world [1], the cameras of the smartphones could potentially be used in place of such technology. Simplified monitoring of growth of tomatoes and other crops could lead to improved crop yield, which could help alleviate economic stress on farmers.

The use of technology as an aid in determining tomato ripeness dates back to 1960 when Hunter Associates Lab was commissioned by the U.S. Department of Agriculture to create an instrument to measure color index of tomatoes directly [6]. The result of that venture was a direct-reading photoelectric tristimulus instrument that generated color coordinates in the Hunter L,a,b color space. Still, distinction of the different stages of ripeness was typically done subjectively through 1983 [19]. By the 1990s and into the mid-2000s, it became more typical to use tristimulus colorimeters in color measurement of tomatoes when information beyond general categories was required [20-22]. Within the past year, published research has included analysis performed using portable Raman spectroscopy [23] and portable infrared spectroscopy [24]. These methods still lean heavily into biological research. If smartphones can be applied to the determination of ripeness, the use of specialized biological research equipment could be circumvented. However, it is necessary for calibration on a device-specific basis so the highest amount of precision is possible. Mapping known RGB and XYZ values has been found to be the best way to do this for smartphones [2]. In this case, that is intended to be done using the tomato color checkers developed in this research.

Methods

Images of the tomatoes were taken at seven stages of ripeness, with more sampling within the orange and red stages. These levels were chosen to determine if the smartphones could detect the subtle differences between stages of near ripeness. The stages were classified as red, dark orange, medium orange, light orange, gold, yellow-green, and green. They did not align with the six ripening stages of the USDA classifications because of the desire for a range of coverage in the reds and oranges [20]. Seven tomatoes were picked from the cherry plants and the grape plants at the same time and were then promptly imaged and measured in the sunlight. The "spectra" of cherry and grape tomatoes are shown in Figure 1a and b, respectively. The tomatoes were then taken indoors and imaged with the same devices and settings under LED light.

(a)

(b)

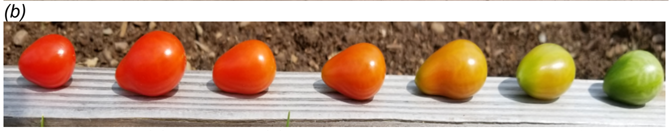


Figure 1: Cherry (a) and grape (b) tomatoes picked at seven stages of ripeness.

Five devices were used in imaging, with images taken with the HDR setting both on and off. If the device had timer capabilities, the timer was used for focusing purposes. The images were taken in quick succession, then the spectral reflectance distributions of the tomatoes were measured using a PR-655 immediately after. The $L^*a^*b^*$ and L^*C^*h values of the tomatoes were calculated using the spectra and D65 for the 2° observer. These measurements were used as the true color of the tomatoes and were compared with the color of the images captured by each device.

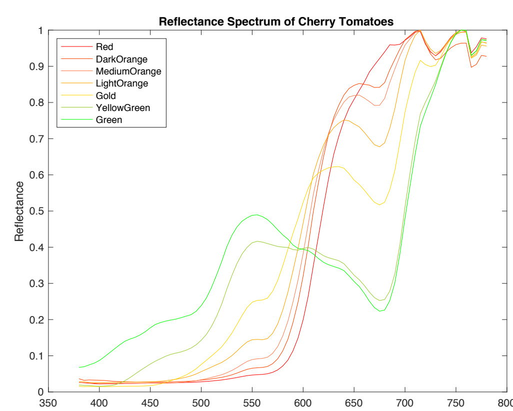
Subsequently, a similar practice of categorizing, measuring, and imaging was implemented using a larger quantity of tomatoes to increase the sample size, also incorporating full-sized tomatoes. This time, though, the measurements and imaging were performed in a light booth under D65 lighting. An example of this is displayed in Figure 2.

Figure 2: A range of tomatoes used in measurement and an example tomato image

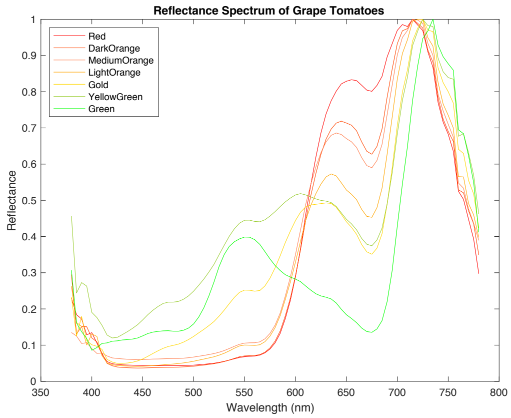
The images were cropped to 250 x 250 px squares of uniform color within each tomato to the best possible degree. Using the small subsections of the image was achievable and necessary to obtain the required uniformity for the relatively small cherry and grape tomatoes. Three squares were taken for each tomato from each device. The mean color of each cropped image was then obtained in MATLAB by converting the sRGB coordinates at each pixel to $L^*a^*b^*$ and averaging them. The colors of the three cropped images for each tomato were then averaged to get the final color value of the tomatoes from each device.

Results

The measured spectral reflectance distributions of the tomatoes are plotted in Figure 3 a-b. For most stages of growth, the measured spectra for both cherry and grape tomatoes have a peak at 550 nm. This peak is highest in the green cherry tomatoes and the yellow-green grape tomatoes, while decreasing through the stages of ripeness until it is nearly or entirely gone in the reddest tomatoes. A characteristic of the spectral reflection distribution of chlorophyll is a peak at 550 nm, so it makes sense that this peak is highest for the green tomatoes [25,26]. Conversely, there is a dip in the spectral reflectance distribution at 670 nm. This dip is due to absorption of light by chlorophyll [27]. While it is deepest in the greenest tomatoes, this dip does not fully disappear until lycopene becomes more concentrated than chlorophyll and the tomato is fully red. Since the decrease is only fully gone in the red tomatoes, determination of this characteristic can be useful in forecasting ripeness, along with gauging the relative reflectance at 550nm.



(a)



(b)

Figure 3: The measured spectral reflectance distributions of the (a) cherry and (b) grape tomatoes.

It may also be noteworthy that, while the reddest cherry and grape tomatoes both had peaks at 715 nm, the cherry tomatoes kept reflecting highly into the infrared region, while reflection into the infrared dropped off for the grape tomatoes. The green cherry tomatoes reflected more highly in the green and yellow wavelengths than the green grape tomatoes did, with peak spectral reflectance distributions of green cherry tomatoes occurring at 760 nm and for grape tomatoes at 735 nm. The spectral reflectance distribution of the gold grape tomato was almost identical to the yellow-green grape tomato spectrum above 635 nm, while the spectral reflectance distribution of the gold cherry tomato was in the middle between the light orange and yellow-green cherry tomato spectra. The biggest differences in spectra between unripe and ripe tomatoes occurred at 550 nm and 670 nm, two wavelengths within the visible range. Th magnitude of these differences suggest that infrared data filtered out by smartphone cameras is not necessary for forecasting ripeness, though it still may be relevant for other applications, such as disease detection.

The measured hue angles for the tomatoes were then compared to the hue angles captured in the images. The relationships between the two corresponding hue angles were then determined by plotting the results for each device. The plots for the cherry tomatoes are displayed in Figure 4 a-e, and the plots for the grape tomatoes are displayed in Figure 5 a-e.

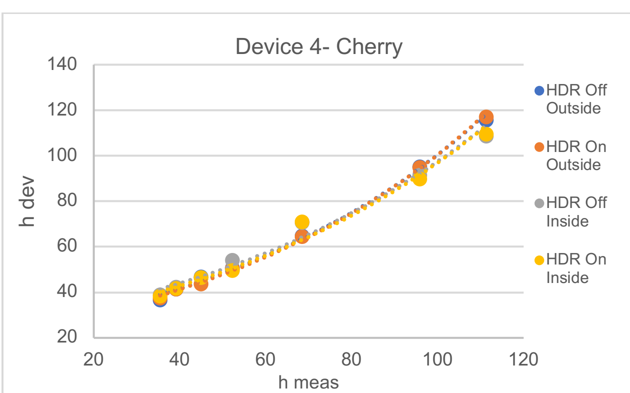


Figure 6: The measured hue angle vs. the captured hue angle of cherry tomatoes for the five devices.

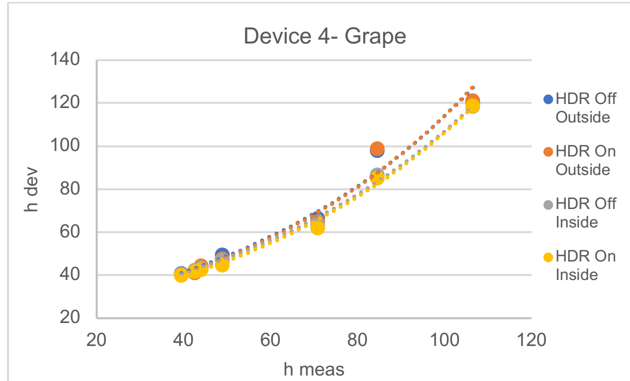


Figure 7: The measured hue angle vs. the captured hue angle of grape tomatoes for the five devices.

Linear, exponential, and power fits of the data were tested; for the majority of cases, it was found that the exponential fit was the most appropriate. The R^2 values for each type of fit for each device are shown in Table 1 a-b. The highest R^2 values for each lighting condition and device are highlighted. The best fit for grape tomatoes was very clearly exponential, aside from Device 5, but there was more variation in peak fit for the cherry tomatoes. While in every case the R^2 is very high, an exponential relationship is preferred because it provides a better fit for the red and oranges shades, which are clustered close together. Because of this, an exponential relationship was also used for the cherry tomatoes. Additionally, the acceleration of the accumulation of lycopene after enough carotenoids have developed and the tomato has reached a pink color [5], which lends biological support to the use of the exponential fit.

Average R^2	HDR Off Outside	HDR On Outside	HDR Off Inside	HDR On Inside
Linear	0.9907	0.9932	0.9896	0.9889
Exponential	0.9767	0.9772	0.9851	0.9785
Power	0.9880	0.9919	0.9837	0.9837

Table 1a: The average R2 coefficients for the relationship between measured hue and hue obtained from the devices for cherry tomatoes.

Average R^2	HDR Off Outside	HDR On Outside	HDR Off Inside	HDR On Inside
Linear	0.9768	0.9742	0.9459	0.9432
Exponential	0.9795	0.9756	0.9650	0.9642
Power	0.9794	0.9740	0.9494	0.9461

Table 1b: The average R2 coefficients for the relationship between measured hue and hue obtained from the devices for grape tomatoes.

The very high correlation to an exponential relationship between the actual hue of tomatoes and the hue captured by various devices indicates that it should be possible to use smartphone images to determine if tomatoes are ripe to be picked, or even plan the harvest ahead of time. The goodness of fit to an exponential relationship varied between devices, lighting conditions, and target tomato, but the agreement was consistently high, with only four peak R^2 values less than 0.97 and all greater than 0.90.

These data were used to make preliminary test targets for use in calibration of images taken in the field. Since the goal for the targets was something lightweight and easily transportable, it was decided to test the feasibility of fabric targets. Fabric would allow the targets to be foldable and easily laid out where needed. Color swatches from the measured values of the cherry tomatoes were printed using an inkjet on three types of fabrics: modern jersey, eco canvas, and fleece. The three fabrics were chosen for the accuracy of color printed on them and their relative opacity to other available fabrics. However, the fabrics were not completely opaque and needed some form of backing to block out all light from being transmitted through from behind. The repeatability of printing the chart on the cloth needs to be evaluated in future work, as does the durability of the targets.

Measurements of the color patches were made with no backing, with white and black fleece, and with white and black felt backings. The white felt and the fleece were found to be too fluorescent for use. While the black felt reduced the overall magnitude of the spectral reflectance distributions of the color patches, it was not fluorescent and provided a more opaque, uniform backing.

With the findings from the preliminary target in place, a more extensive color checker target was created. It is displayed in Figure 8. The colors in the first four columns were taken from the spectroradiometric measurements transformed into $L^*a^*b^*$ values. Row 1 is the "spectrum" of cherry tomato colors, row 2 is grape tomatoes, and row 3 is full-sized tomatoes. Colors from the X-Rite ColorChecker were included in order to assess the entire gamut of the smartphone cameras. It is anticipated that more images of tomatoes with the chart present will be taken in a controlled greenhouse setting to assess the usability of the chart. Depending on the performance of the cloth chart with black felt backing, other possibilities for the chart may be investigated. The possibilities may include small, ceramic charts. Ceramic charts, while glossy, are easier to clean, which might be necessary for a target taken into the field. Ceramic tiles may also be more durable than cloth targets.

Figure 8: The proposed tomato color checker chart.

Conclusion

A relationship between the measured and imaged hue angles of two kinds of tomatoes for five handheld devices was found. While linear and power fits were very good, an exponential fit was shown to be best for grape tomatoes. While there would need to be further study with a much more extensive selection of devices and target fruit before being used by the public, the preliminary results of this study suggest that further extension of this work would not be unwarranted. If the methodology can be accurately applied to tomatoes, that implies that it would be possible to use for other fruits that change color as they ripen, such as coffee cherries or grapes. Other possibilities could also be opened, such as assessment of soil quality, irrigation, and fertilization programs. Even pest and disease detection could be possible with further development.

References

[1] World Bank, "World Development Report 2016: Digital Dividends," Washington, DC: World Bank, 2-16.

[2] M. Nixon, F. Outlaw, L.W. MacDonald, and T.S. Leung, "The importance of a device specific calibration for smartphone colorimetry," in Twenty Seventh Color and Imaging Conference, Paris, France, 2019.

[3] F.J. Francis, "Quality as Influenced by Color," Food Qual. and Preference, vol. 6, pp. 149-155, 1995.

[4] R. Arias et al., "Correlation of Lycopene Measured by HPLC with the L*, a*, b* Color Readings of a Hydroponic Tomato and the Relationship of Maturity with Color and Lycopene Content," Jour. Ag. and Food Chem., vol. 48, no. 5, pp. 1697-1702, 2000.

[5] S. Brandt, Z. Pék, E. Barna, A. Lugasi, and L. Helyes, "Lycopene content and colour of ripening tomatoes as affected by environmental conditions," Journal of the Science of Food and Agriculture, 86, pp. 568-572, 2006.

[6] E. Garcia and D. M. Barrett, "Assessing Lycopene Content in California Processing Tomatoes," Jour. Food Processing and Preservation, vol. 30, pp. 56-70, 2006.

[7] R. S. Hunter and J.N. Yeatman, "Direct-Reading Tomato Colorimeter," Jour. Optical Soc. of America, vol. 51, no. 5, 1961.

[8] L. Helyes, A. Lugasi, and Z. Pék, "Effect of natural light on surface temperature and lycopene content of vine ripened tomato fruit," Canadian Jour. Plant Sci., vol. 87, no. 4, pp. 927-929, 2007.

[9] R. Arias, T.C. Lee, D. Specca, and H. Janes, "Quality Comparison of Hydroponic Tomatoes (Lycopersicon esculentum) Ripened On and Off Vine, Jour. Food Sci., vol. 65, no. 3, pp. 545-548, 2000.

[10] Z. Pék and L. Helyes, "Color Changes and Antioxidant Content of Vine and Postharvest-ripened Tomato Fruits," HortScience, vol. 45., no. 3, pp.466-468, 2010.

[11] M.L.A.T.M. Hertog et al., "The impact of biological variation on postharvest behaviour of tomato fruit," Postharvest Bio. and Tech., vol. 34, pp. 271-284, 2004.

[12] N. J. Stehr, “Drones: The Newest Techonology for Precision Agriculture,” Am. Soc. of Agronomy, vol. 44, no. 1, pp. 89-91, 2015.

[13] A. S. Natu and S.C. Kulkarni, “Adoption and Utilization of Drones for Advanced Precision Farming: A Review,” International Jour. on Recent and Innovation Trends in Computing and Communication, vol. 4, no. 5, pp. 563-565, 2016.

[14] K. Moskvitch, “Take off: are drones the future of farming?” Engineering and Technology, vol. 10, no. 7, pp. 62-66, 2015.

[15] U.S. Department of Transportation, “Unmanned Aircraft Systems: Getting Started,” Federal Aviation Administration, https://www.faa.gov/uas/getting_started/, 5/17/19.

[16] C. Okali and J. Sumberg, “Quick Money and Power: Tomatoes and Livelihood Building in Rural Brong Ahafo, Ghana,” IDS Bulletin Special Issue: Young People and Agriculture in Africa, vol. 43, no. 6, pp. 44-57, 2012.

[17] S. Brown and G. Kennedy, “A case study of cash cropping in Nepal: Poverty alleviation or inequity?,” Agriculture and Human Values, vol. 22, no. 1, pp. 105-116, 2005.

[18] S. Gebreselassie, “Helping small farmers to commercialise: Evidence from growing onion and tomatoes for sale in central Ethiopia,” Future Agricultures, https://www.futureagricultures.org/,https://assets.publishing.service.gov.uk/media/57a08a77e5274a27b20005e7/Commercialisation_Research_Update_003.pdf, 2003.

[19] G.E. Hobson, P. Adams, and T.J. Dixon, “Assessing the colour of tomato fruit during ripening,” Jour. Sci. of Food and Ag., vol. 34, no. 3, pp. 286-292, 1983.

[20] M.C. D’Souza, S. Singha, and M. Ingle, “Lycopene Concentration of Tomato Fruit can be Estimated from Chromaticity Values,” HortScience, vol. 27, no. 5, pp. 465-466, 1992.

[21] A.F. Lópex Camelo and P.A. Gómez, “Comparison of color indexes for tomato ripening,” Horticulura Brasileira, vol. 22, no. 3, pp. 534-537, 2004.

[22] G.T. Dodds, J.W. Brown, and P.M. Ludford, “Surface Color Changes of Tomato and Other Solanaceous Fruit during Chilling,” Jour. Amer. Soc. Hort. Sci., vol. 116, no. 3, pp. 482-490, 1991.

[23] J. Trebolazabala et al., “Portable Raman spectroscopy for an in-situ monitoring the ripening of tomato (Solanum lycopersicum) fruits,” Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy, vol. 180, pp. 138-143, 2017.

[24] P. Skolik, C.L.M. Morais, F.L. Martin, and M.R. McAinsh, “Determination of developmental and ripening stages of whole tomato fruit using portable infrared spectroscopy and Chemometrics,” BMC Plant Bio., vol. 19, 2019.

[25] A.A. Gitelson and M.N. Merzlyak, “Signature Analysis of Leaf Reflectance Spectra: Algorithm Development for Remote Sensing of Chlorophyll,” Jour.Plant Physiology, vol. 148, nos. 3-4, pp. 494-500, 1996.

[26] E.R. Hunt Jr. et al., “A visible band index for remote sensing leaf chlorophyll content at the canopy scale,” International Jour. Applied Earth Obs. and Geoinformation, vol. 21, pp. 103-112, 2013.

[27] G. MacKinney, “Absorption of light by chlorophyll solutions,” Jour. Bio. Chem., vol. 140, pp. 315-322, 1941.