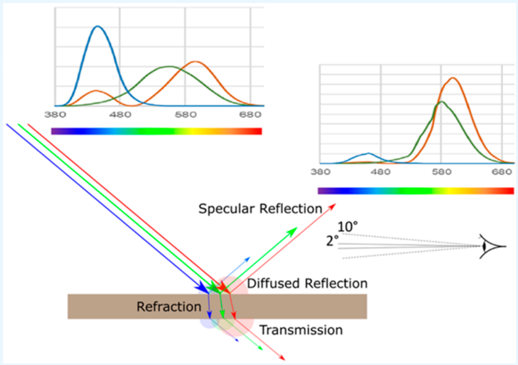
ACS OMEGA
http://pubs.acs.org/journal/acsodf
Review

Polymer Color Intelligence: Effect of Materials, Instruments, and Measurement Techniques – A Review

Sachin Agate, Austin Williams, Joseph Dougherty, Orlin D. Velev, and Lokendra Pal*

Cite This: *ACS Omega* 2023, 8, 23257–23270
Read Online

ABSTRACT: Transparent polymers and plastics are used to create molded parts and films for many applications. The colors of these products are of great importance for the suppliers, manufacturers, and end-users. However, for simplicity of the processing, the plastics are produced in the form of small pellets or granules. The predictive measurement of the color of such materials is a challenging process and needs consideration of a complex set of factors. A combination of color measurement systems in transmittance and reflectance modes need to be used for such materials, along with the techniques for minimizing the artifacts based on surface texture and particle sizes. This article provides an extensive overview and discussion of the various factors that can affect the perceptive colors and the methods used for the characterization of the colors and minimizing the measuring artifacts.



INTRODUCTION:

Polymeric materials are ubiquitous in day-to-day life. Textiles,[1] fibers,[2] coatings,[3] utensils,[4] durable products,[5] and food ingredients (e.g., starch)[6] are a few examples of the applications of polymers in consumer products and elements of everyday life. Every category of application needs certain performance from the polymers such as heat or cold resistance, flexibility, transparency or opacity, color, and machinability. The optical properties of the polymers are the key to applications involving photonics and aesthetics. Some examples in the photonics field include fiber optics and encasing of the optical elements like LED, displays, and UV shieldings. The color also plays an important role in the perception of the aesthetic properties of products such as coatings, films, or containers made from polymers. The appearance of such products can directly affect the customers' choice for purchasing the product. Therefore, in plastic molding applications, the color of the polymer needs to be characterized precisely and maintained consistently.

The process of plastic molding is performed by melt extrusion of plastic pellets into preformed shapes.[7] The color of the final shape is the one that is of interest to the processing industry. To maintain this color, the pellet manufacturers need to measure and to control color of the pellets at their manufacturing facility. As the pellets are small in size, their mass can show prominent edge effects, light refraction and scattering, and drastic changes in color appearances resulting from their shape and light refraction. The direct methods of color measurement require to convert the pellets into the product and measure the color. Another method includes the estimation of the product color by measuring the pellet color. This article discusses various instruments and methods of color measurements that are available in the industry. Some instrument manufacturers and plastic industry experts have listed the procedure of plastics color measurement and the suitable instrument geometry for them.[8] Similarly, articles are available on how plastic color measurement can help in recycling and sorting of plastics.[9] However, there is a lack of in-depth knowledge of many factors that can affect color measurements.

UNDERSTANDING THE CONCEPT OF COLOR MEASUREMENT:

A color is a human perceptual concept related to human vision. Human vision is an excellent tool for evaluating the surroundings and assessing situations. The analysis of optical information is done in the brain and compared with previous experiences. This method is seamless, and most of the times it helps in quick judgment of possible threats or advantageous situations. All the color analysis in the brain is performed on a relative basis, where a visual deviation from a previous reference is compared. Thus, the color values are subjective to every human's capability of receiving the visual stimulus and relating it to previous experiences.

Received: December 29, 2022
Accepted: May 24, 2023
Published: June 20, 2023

https://doi.org/10.1021/acsomega.2c08252
ACS Omega 2023, 8, 23257–23270

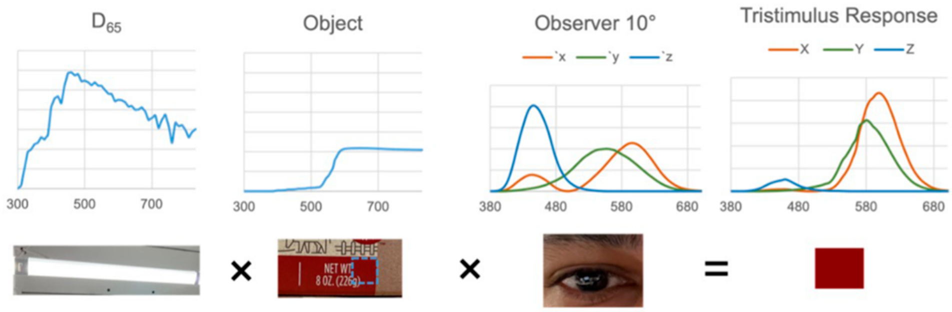


Figure 1. Generic scheme of color generation. The spectral outcome of the source, response of the object, and stimulating sensitivity of the observer visual system combine to form a tristimulus response of the color.

While this perceptual analysis provides rapid solutions for practical application, they can also be used for creating illusions of colors and their brightness.[10,11] Therefore, finding a consensus for fine color variation is difficult. People therefore rely on instrumentation to quantify the incident light and mathematically transform the spectral intensities into an empirical visual function. The calculated visual data is then assumed to closely match the real life visual color perception. Such data can then be shared, and chances of conflicting opinions are virtually eliminated. This method, however, does not guarantee the provision of true information on an object's spectral responses as occasionally two different spectral responses can result in similar color values.

In 1913, the International Commission on Illumination (CIE) was founded to study vision, color, illumination, and images. Their work provided a generalized standard function for the observer's visual stimulus for color perception. The first color space designed by CIE's formulas was CIE XYZ space in 1931. Later in 1964, the theory on observer functions was reevaluated. Various factors such as standard illuminants and color spaces (CIELAB and CIELUV) were developed based on these studies. Their role will be discussed later in this article.

COLOR VISION AND STANDARD OBSERVER

The source of color is the electromagnetic waves capable of stimulating the visual system of a human. Out of the vast range of electromagnetic radiation, only a tiny band is capable of being detected by human vision. The visual spectrum of light covers the wavelength range from 380 to 780 nm. Lower wavelengths are high-energy UV radiation, X-rays, and γ-rays, and higher wavelengths are infrared, microwave, and radio waves.

The human eye has two types of light receptors. One is rod-shaped cells that are highly sensitive to light. However, they contribute negligibly to the detection of color and operate in dim light. The second type of receptor is the cone cells. These cells are specialized in detection of three major bands of light mainly identified as short (blue), medium (green), and long (red) wavelengths.[12,13] The combined signal of these photodetectors is interpreted as an image and its color distribution. The rod cell count in a human eye is around 120 million and the cone cell count is around 6 million.[14] The cone cells are concentrated at the central region of the retina. The maximum peaks of sensitivity for visible light referred to as short, medium and long wavelengths are, respectively, 420−440, 530−540, and 560−580 nm.[15]

In 1931, CIE considered that human color vision is mainly concentrated at a 2° region at the center of the fovea. Later, a larger field of view (10°) was studied for color vision.[16] Thus, in 1964, the standard observer was considered as a 10° observer. Based on the selected model, color matching functions were developed to quantify color. Figure 1 shows how colors are generated by the combination of light source, object, and observer.

Standard Illuminants: The illuminant plays an important role in the color of the object. The object being observed is generally not a source of light itself. The light source produces light and directs it toward the object. This light gets reflected by or transmitted through the object by its characteristic surface and bulk properties. The standard light spectrum generated by known light sources is called an illuminant. Thus, the illuminant is a spectral function and can be converted into another illuminant by mathematical transformation. The color of any object is based on how much of the incident light of different wavelengths it can redirect to the observer. The absence of spectral wavelengths in the illuminant can produce varying color effects. Various standard illuminants are defined by CIE for mimicking various lighting conditions as A−F-series illuminants, which are indicated in Table 1.[17]

Calculating Color Values. Color vision or the capability of spectral interpretation by a standard observer, object spectral modulation properties, and the spectrum of the standard illuminant come together to produce a color perception of the object. The following equations provide the CIE method of calculating tristimulus values of the color signal registered by the standard observer.[17] The *XYZ* equations reflect the dependence of the color perception on the spectral curve of the illuminant, spectral reaction of the object, and the observer's eyes' spectral sensitivity (color matching functions eqs 1−4)

$$X = k \int_{\lambda} R(\lambda) S(\lambda) \overline{x}(\lambda)\, d\lambda \tag{1}$$

$$Y = k \int_{\lambda} R(\lambda) S(\lambda) \overline{y}(\lambda)\, d\lambda \tag{2}$$

$$Z = k \int_{\lambda} R(\lambda) S(\lambda) \overline{z}(\lambda)\, d\lambda \tag{3}$$

$$k = \frac{100}{\int_{\lambda} S(\lambda) \overline{y}(\lambda)\, d\lambda} \tag{4}$$

where X, Y, and Z are tristimulus values, $R(\lambda)$ is reflectance, transmittance or radiance factor (scale of 0 to 1 for perfect reflecting diffuser), $S(\lambda)$ is relative spectral power of CIE standard illuminant, $\overline{x}(\lambda)$, $\overline{y}(\lambda)$, and $\overline{z}(\lambda)$ are color-matching functions of the CIE standard observer, k is the normalizing factor, and λ is the wavelength ranging from 360 to 830 nm

https://doi.org/10.1021/acsomega.2c08252
ACS Omega 2023, 8, 23257−23270

Table 1. List of Standard CIE Illuminants.

Illuminant Series	Illuminant	Color Temperature (K)	Comment	Ref
A	A	2855.6 (~2856)	Incandescent tungsten filament (old standard)	17
		2848	Incandescent tungsten filament (new study)	18
B	B	4900	Direct daylight	19
C	C	6774	Shady daylight	17
D	D50	5000	Daylight	20
	D55	5500		20, 21
	D65	6504 (6500)		17
	D75	7500		20
E	E	5455	Hypothetical radiator with equal power for all spectral wavelengths	18, 19
F	F1-F6		Normal fluorescent	18
	F7-F9		Broadband fluorescent	
	F10-F12		Three narrow band fluorescent	
	FL3.1-FL3.3		Standard halo fluorescent	
	FL3.4-FL3.6		DeLuxe fluorescent	
	FL3.7-FL3.11		Three narrow band fluorescent	
	FL-3.12-FL3.14		Multiband fluorescent	
	FL3.15		D65 simulation	

For practical purposes, the wavelengths are typically sampled at regular intervals of 5 or 10 nm, and the integration is approximated to the summation. The tristimulus values can further be converted to other color spaces known as CIELAB and CIELUV, which are more uniform than CIEXYZ color space. The formulas for transformation of color spaces are defined by CIE, and they are specified in ASTM standard E308 for color measurements.[17] It should be noted that the reflectance or transmittance of an object is also affected by the object geometry and the illumination angle. Therefore, these factors are critical during color measurement and discussed in the measurement geometry section.

FACTORS AFFECTING THE MEASURED COLOR VALUES

Illuminant's Spectrum. As seen in the *XYZ* calculations, the illuminant plays an important role. If a certain wavelength of light is missing in the illuminant, the stimuli are null for that wavelength. Therefore, an object can show different colors with two different illuminants. This is known as metamerism.[22] There are other factors affecting metamerism such as observer's inherent color sensitivity, field of view (viewing angle), and instrument geometry.[23] More details on field of view and geometry are given later. Metamerism can also be a result of an observer's visual sensitivity. However, for the standard observer, this condition can be ignored.

Sensitivity of the Instrument: Colors are measured using spectrophotometers or colorimeters.[24] The difference is the sensitivity range on the spectral scale. The spectrophotometers record the visible wavelengths by sampling them into small bands. The sampling frequency determines the accuracy of data collection. Such data can then be transformed for color measurement. The colorimeters differ in their data collection methods. They have three or more filters for red, green, and blue bands of light. Thus, the collected data is preprocessed by physical elements, and further mathematical processing is limited. With the advent of digital photography, researchers are working on the camera's inherent light filtering capabilities to capture the RGB data of the image and estimate the colors of the objects.[25,26] This technique is still not perfected and needs a standard color chart to be included in every image as a reference for estimating the lighting conditions and true colors of the object.

Color Standards Used for Calibration. Every reflectance spectrometer is generally calibrated using a set of standard reflectance tiles. The first standard is a black reference. Any error in this value results in a constant offset to the whole spectrum. Therefore, the measured value ($R_m(\lambda)$) can be adjusted by adding a constant (B_0) to obtain a true spectrum ($R_t(\lambda)$) (eq 5).[27]

$$R_t(\lambda) = R_m(\lambda) + B_0 \tag{5}$$

Another source of error could arise from the variation in the white tile (reference) due to surface defects, aging, and probe alignment.[27] This can be adjusted by adding a constant percentage (B_1) to the measured value (eq 6).

$$R_t(\lambda) = R_m(\lambda) + \left(\frac{100 + B_1}{100}\right) \tag{6}$$

Measurement Geometry. The most accurate colors are measured using spectrophotometers. The geometry of viewing is a prime factor for the appearance of any color. The object being viewed can diffuse the light or not. For transparent objects, if the light is not diffused, the illuminating beam can directly strike the eye or the sensor. For the reflection systems, the gloss of the object can cause a change in the perception of the color. To address these conditions, various viewing geometries can be chosen. In common practice, geometries like 0/45 (0:45), 45/0 (45:0), 45:0 a, 45:0 c, 45:0 x, 0/d (0:d), d/0 (d:0), d/8 (d:8), de/8 (de:8), and di/8 (di:8) are used (Figure 2) for reflection spectrophotometers.[28] Additionally, in-line illumination and multiangle reflection are also used. In the 45/0, the first angle (or symbol) is the illuminant angle, and the second angle is the observer/sensor angle. Thus, in 0/45 geometry, the illuminant is at 0° with respect to the normal of the object's surface, while the sensor is at 45° angle from the normal. The letters "a", "c", and "x" indicate illumination as annular, circumferential, and single azimuth angle, respectively.

In d/0, 0/d, d/8, de:8, di:8 geometries, the "d" indicates that diffused light is incident to or given off the object ("d" can apply to the input or output). The diffused light is obtained using a white diffuse reflective surface inside a sphere. The sphere causes multiple reflections of the incident light minimizing the specular component of the light. Such spheres are known as integrating spheres.[29,30] The d/8 geometry can be seen for many instruments, where the sensor is at 8° angle to the normal. When specular reflections are included in diffuse geometry, they can be specified as "di" and when they are excluded; the indication is "de". The examples of different surface types and instrument geometries are shown in Figure 2.

Although these geometries provide good color measurements for uniform, optically flat surfaces, they fail for reflective or nonuniform optical surfaces. Metals[31] and pearlescent surfaces,[32] for example, need a special measurement condition known as multiangle aspecular measurement. The illuminant is

https://doi.org/10.1021/acsomega.2c08252
ACS Omega 2023, 8, 23257−23270

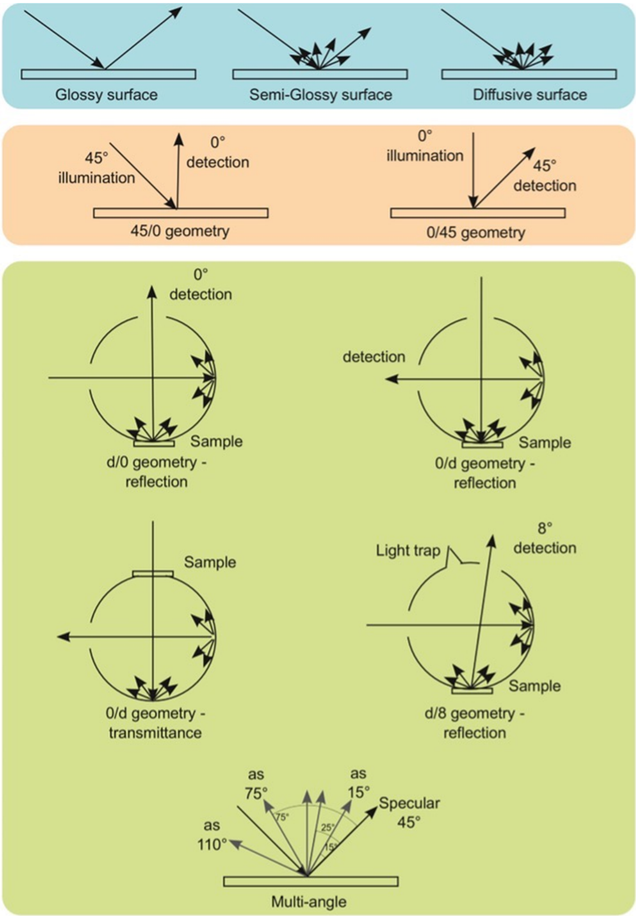


Figure 2. Types of surfaces and different classes of instrument geometries used in color measurement systems.

at 45° to the normal, and the specular reflection comes at −45° in the plane. The negative sign indicates that it is away from the normal on the other side. Measuring angles from this specular reflection toward the normal and crossing the normal are positive angles with respect to the specular reflection. Typically, 15°, 25°, 45°, 75°, and 110° reflections are recorded in multiangle geometry.[31] Illumination angles can change from 45° to 15° or 65° in pearlescent materials, while the aspecular angles can be positive or negative.

The multiangle color measurement is also applicable for materials with iridescent colors.[33] They show angle-dependent colors both for the viewing and the illumination angles. In such cases, the spectrogoniometer is a useful tool. The application of such an instrument may not be limited to the iridescent colors. The number of readings by a spectrogoniometer can be exceptionally high if every combination of the incident and reflection angle is to be considered. Thus, its applications can be very limited and time-consuming. Robotic tools are extremely useful in such cases.[34]

Measurement Area/Field of View. Color measurement devices are designed to view various sample sizes based on the application. Sometimes, the noise and variation in colors is an intrinsic property of the object. In that case, a large sampling area effectively normalizes all color variations over that area. To mimic human vision, a viewing angle of 2° or 10° need to be maintained. However, for various reasons, the aperture size may need to be changed; e.g., an object that is supposed to be viewed from a distance of a couple of feet from an observer vs an object that is viewed from several meters of distance will have different sampling areas for the color measurements. A system with high variability such as mottled print, metallic paints, plastic granules, etc. would be preferably sampled with as large an area as possible. The object curvature may also limit the aperture size. Thus, as the measurement area increases or decreases the measured color values will change. Spectrophotometers are available with sampling areas from 2 mm diameter to 50 mm diameter as shown in Table 2.

The importance of the measurement area is evident when one encounters the structural/iridescent colors, where the spectral response is based on the number of objects interacting with the light beam. However, in some cases in scientific and forensic sciences, the sample sizes might be in micrometer ranges. To analyze the spectral responses of such samples, micrometer coupled spectrometers are used.[35] Such instruments use in-line geometry, and the viewing angles might not match the standard observer angles. The microspectrophotometers can analyze biological samples and fluorescent materials.

Object Structure. The color of an object originates from its chemical properties and physical state. When an object is illuminated, its ability to modify the light causes appearance changes. The molecular packing and large-scale surface parameters are well-known to cause variation in light's interaction. Thus, the color values can change for materials with variation in factors discussed below.

Chemical Properties. The color of the material is based on chemical groups that can interact with light. These groups are known as chromophores (Figure 4). Clear transparent materials lack such chromophores, while they are present in colored materials. Another type of groups is the fluorophores, which respond to high energy wavelengths and produce a fluorescent light. Such materials can change colors if exposed to UV wavelengths as seen in the optical brightening agents (OBA).

Phases in the Material. Transparent or translucent objects can have multiple crystalline phases. Composites can show aggregation and cause heterogeneous structures resulting in variation of refractive indices.[36] For small particulates, air trapped between individual particles can cause light scattering. This results in unexpected light modulation and color changes.

Object Shape. The edges of any particle can intensify the light scattering. The smaller the object, the greater are the relative contributions of its edges (Figure 4). Light diffraction at the edges results in the variation of brightness. In non-spherical particle systems, the polarization of incident light and the axial orientation of the particles can change the colors.[37]

Object Size and Scattering. As stated in the previous paragraph, the object shape contributes to the number of edges interacting with light as does the object size. Colors may be rendered from the Rayleigh scattering mechanism where the particle size is smaller than the wavelength of the light.[38] Materials with larger particles may show Mie scattering.[39] There are also other scattering mechanisms such as Raman scattering.[40] In certain situations, where the object takes shape of thin films, it can lead to thin film interference effects and color variations.[41]

Molecular and Particle Arrangement: A subwavelength structure made by the ordered molecular arrangement results in a crystal lattice capable of diffracting light, which is explained by Braggs' law.[42] For such crystalline materials, the polymorphism[43,44] changes the color due to difference in crystal diffraction patterns. Similar to molecular arrangement,

https://doi.org/10.1021/acsomega.2c08252
ACS Omega 2023, 8, 23257−23270

the ordered nanocrystal arrangement, also identified as a photonic crystal, shows color iridescence based on the diffraction of the light.[45]

Surface Texture. Smooth objects do not contribute to diffusion of light; rather, the light is mostly specularly reflected. The surface smoothness levels cause specular reflection of the light, resulting in very little light being scattered in other directions. The object can therefore appear darker when viewed at angles other than the specular angle. If the object has any texture, both diffusion and scattering of the light may take place.

Pathlength of the Light. The object of interest for the color measurements can be a single entity or a system of particles suspended in another media such as air or a polymer matrix. In both cases, the number of light-interactive species are directly responsible for the appearance of color. Those species can be chromophores or particle edges causing differences in refractive indices. For a homogeneous system, the path length will be directly related to the physical length of the light traveling through it. In most reflective systems, this effect might be hard to quantify, but in transmission material, a user can easily observe the effect by changing the thickness of the material/system (Figure 3).

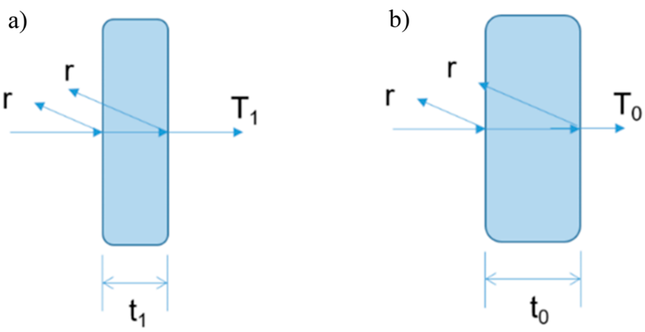


Figure 3. Object and light beam visualization for path length correction. (a) Transmission "T_1" measured for the object with thickness "t_1". (b) Ideal object with thickness "t_0" and transmittance "T_0". "r" = reflectance at the interface.

In advanced color processing, a thickness correction can be calculated[46,47] based on a number of parameters, including: t_0 = ideal thickness of the object, t_1 = thickness of the object, T_1 = measured transmittance, T_0 = corrected transmittance, r = reflectance at the surface, and n = refractive index of the material.

The reflectance and the changes in transmittance can be calculated by eqs 7−9.

$$r\ (\%) = 100 \times \left(\frac{n-1}{n+1}\right)^2 \tag{7}$$

$$T_1^{'} = \frac{T_1}{\left(1 - \frac{r}{100}\right)^2} \tag{8}$$

$$T_0 = 100 \times \left(\frac{T_1^{'}}{100}\right)^{t_0/t_1} \times \left(1 - \frac{r}{100}\right)^2 \tag{9}$$

Beer−Lambert's equation[47] can be implemented to determine the absorption losses of the light (eq 10)

$$A = \varepsilon C t = -log_{10} T \tag{10}$$

where ε = molar absorptivity of the material, C = concentration of light absorbing species, A = absorbance of the material, and T = transmittance.

Refractive Index. As discussed earlier, various physical conditions of the object of interest can affect its color perception. It is known that gold colloids can change colors based on the refractive index of the medium.[48] When refractive indices of the particles and liquid are close to each other, the transmittance of the system is maximal. Various single-component or multicomponent liquids can be used, containing components such as zirconia nanoparticles,[49] silicones, glycerol, and synthetic oils[50] for variation in the refractive index of the medium.

In practice, the modification of refractive index (RI) of the system can be applied in the field of microscopy to improve or reduce the contrast of the object.[51] It is also being studied for suppression of the scattering of light.[52] The RI matching techniques are used for measuring the refractive index of nanoscale particles, which are rather hard to form a continuous bulk phase.[53]

Polarization of light. Light polarization has great importance in the color appearance for any object. The light polarized at the reflecting surface may lead to a change in color appearance. At the Brewster's angle,[54,55] the amount of polarized reflection and transmittance can change; hence, the color of the object can change (Figure 4). Polarization color

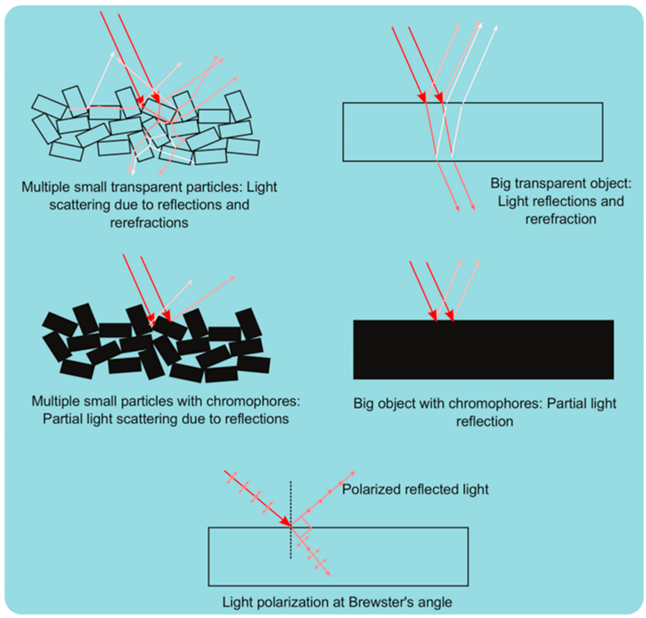


Figure 4. Effects of particle sizes, orientation, surface reflections, presence of chromophores, and Brewster's angle on reflected and transmitted light.

tuning can be used for phase-changing displays.[36] In the case of plastics, the internal stresses may cause photoelastic effects[56,57] and lead to color changes under polarized light.

■ OPERATING PROCEDURES FOR THE COLOR MEASUREMENT

Color measurements can be performed in three modes: off-line; at-line; and in-line measurements.[58] The off-line mode is a standard operating procedure followed for most measurements. The samples are prepared in a batch and then measured

https://doi.org/10.1021/acsomega.2c08252
ACS Omega 2023, 8, 23257−23270

Table 2. Spectrophotometers and Their Capabilities That Are Useful for Measuring Plastic Colors in Powder, Granule, Sheet, and Suspensions[a]

Mfr (Inst Family), Spectrometer Name	Type, Sample Type, Specialty	Range (mm), Measured Spot Diameter (R) or Optical Path Length (T) (mm)	Geometry, Light Source, Spectrum Range (nm), Sampling Frequency (nm)	Source
Thermo Fisher Scientific (ND 2000), ND-2000-US-CAN	T, Liquid, No cuvette	NA, 1	Inline (0), Xenon, 190−840, 1	ND-2000-US-CAN. https://www.neobits.com/thermo_fisher_scientific_nd_2000_us_can_2000_1_p9836674.html?atc=gbp&gclid=Cj0KCQjwka_1BRCPARIsAMlUmEpSnM52HBaLqxhXDBavXH1VhBg61F74SPcvBQZiUai24635j3vJnAUaAvEkEALw_wcB (accessed May 08, 2020).
Thermo Fisher Scientific (ND 2000), NanoDrop 2000c	T, Liquid, Stirring and heating cuvette	NA, 1−10	Inline (0), Xenon, 190−840, 1	ND 2000. https://www.thermofisher.com/order/catalog/product/ND-2000#/ND-2000 (accessed May 08, 2020).
Ocean Optics/Ocean insight (Flame), Flame fiber optic UV−vis	T, Liquid, User interchangeable slits (5, 10, 25, 50, 100, 200 μm), external cuvettes	NA, 10	Inline (0), External deuterium tungsten, 200−850, 1.5−3	Flame fiber optic UV−vis/VIS-NIR. https://shop.spectrecology.com/product/flame-uv-vis-fiber-optic-spectrometer-200-850nm/?attribute_pa_options=es-enhanced-sensitivity-standard&attribute_pa_detector=toshiba-3648&gclid=Cj0KCQjwka_1BRCPARIsAMlUmEp-6HMeSyhzbG9tvkcrGhU2gn8nnMsv4tW6gTVRraZDyXnKJsdRDR8aAjXyEALw_wcB (accessed May 08, 2020).
Ocean Optics/Ocean insight (Flame), Flame fiber optic Vis-NIR	T, Liquid, User interchangeable slits (5, 10, 25, 50, 100, 200 μm), external cuvettes	NA, 10	Inline (0), External deuterium tungsten, 350−1000, 1.5−3	Flame fiber optic UV−vis/VIS-NIR. https://shop.spectrecology.com/product/flame-uv-vis-fiber-optic-spectrometer-200-850nm/?attribute_pa_options=es-enhanced-sensitivity-standard&attribute_pa_detector=toshiba-3648&gclid=Cj0KCQjwka_1BRCPARIsAMlUmEp-6HMeSyhzbG9tvkcrGhU2gn8nnMsv4tW6gTVRraZDyXnKJsdRDR8aAjXyEALw_wcB (accessed May 08, 2020).
Ocean Optics/Ocean insight (Flame), FLAME-ABS-UV−vis	T, Liquid, User interchangeable slits (5, 10, 25, 50, 100, 200 μm), external cuvettes	NA, 10	Inline (0), External deuterium tungsten, 200−850, 1.5−3	FLAME-ABS-UV−vis/FL/Reflectance-Vis https://www.spectrecology.com/flame-spectrometer/ (accessed May 08, 2020).
Ocean Optics/Ocean insight (Flame), FLAME-FL	T, Liquid, User interchangeable slits (5, 10, 25, 50, 100, 200 μm), external cuvettes	NA, 10	Inline (0), External tungsten halogen, 350−1000, 1.5−3	FLAME-ABS-UV−vis/FL/Reflectance-Vis https://www.spectrecology.com/flame-spectrometer/ (accessed May 08, 2020).
Ocean Optics/Ocean insight (Flame), Flame-REFLECTANCE-VIS	R, Solid, User interchangeable slits (5, 10, 25, 50, 100, 200 μm), external cuvettes	NA	45/0, Specular and 30/0, −, 350−1000, 1.5−3	FLAME-ABS-UV−vis/FL/Reflectance-Vis https://www.spectrecology.com/flame-spectrometer/ (accessed May 08, 2020).
Overstock lab equipment (Scilogex), Scilogex SP-V1000	T, Liquid	NA, 5−100	Inline (0), Tungsten, 325−1000, 4	Scilogex SP-V1000. https://www.overstocklabequipment.com/ProductDetails.asp?ProductCode=SCI-401021010009&gclid=Cj0KCQjwka_1BRCPARIsAMlUmEpICpVUR2DhhdMaDFmA_0dYsi3THpImiq787PY9P28fHJDWHymmCPEaAhtjEALw_wcB (accessed May 08, 2020).
Overstock lab equipment (Scilogex), Scilogex SP-V1100	T, Liquid	NA, 5−100	Inline (0), Tungsten, 320−1100, 2	Scilogex SP-V1100. https://www.overstocklabequipment.com/Scilogex-SP-V1100-Spectrophotometer-p/sci-401022010009.htm (accessed May 08, 2020).
Overstock lab equipment (Scilogex), Scilogex SP-UV1100	T, Liquid	NA, 5−100	Inline (0), Tungsten, deuterium, 190−1100, 2	Scilogex SP-UV1100. https://www.overstocklabequipment.com/Scilogex-SP-UV1100-Spectrophotometer-p/sci-401012010009.htm (accessed May 08, 2020).
X-rite (Ci), Ci7800	R/T, Solid, 4 + 1 apertures	NA, 2.5, 5, 10, 19	d/8, Pulsed xenon, 360−780, 5, 10, 20	Ci7800. https://www.xrite.com/categories/benchtop-spectrophotometers/ci7800 (accessed May 08, 2020).
X-rite (Ci), Ci7600	R/T, Solid, 3 + 2 apertures	NA, 2.5, 5, 10, 19	d/8, Pulsed xenon, 360−750, 10, 20	Ci7600. https://www.xrite.com/categories/benchtop-spectrophotometers/ci7600 (accessed May 08, 2020).
X-rite (Ci), Ci7860	R/T, Solid, 4 + 1 apertures	NA, 2.5, 5, 10, 19	d/8, Pulsed xenon, 360−780, 5, 10, 20	Ci7860. https://www.xrite.com/categories/benchtop-spectrophotometers/ci7860 (accessed May 08, 2020).
X-rite (Ci), Ci4200	R, Solid	NA, 8	d/8, Gas filled tungsten lamp and UV LED, 400−700, 10	Ci4200. https://www.xrite.com/-/media/xrite/files/literature/l10/l10-400_l10-499/l10-479_ci4200_sell_sheet/l10-479_ci4200_en.pdf (accessed May 08, 2020).
X-rite (Ci), Ci4100	R, Solid	NA, 8	d/8, Gas-filled tungsten, 400−700, 10	Ci4100. https://www.xrite.com/categories/benchtop-spectrophotometers/ci4100 (accessed May 08, 2020).

https://doi.org/10.1021/acsomega.2c08252
ACS Omega 2023, 8, 23257−23270

Table 2. continued

Mfr (Inst Family), Spectrometer Name	Type, Sample Type, Specialty	Range (mm), Measured Spot Diameter (*R*) or Optical Path Length (*T*) (mm)	Geometry, Light Source, Spectrum Range (nm), Sampling Frequency (nm)	Source
X-rite (Ci), Ci64	R, Solid, Portable	NA, 4, 8, 14	d/8, Gas-filled tungsten, UV LED, 400−700, 10	Ci64. https://www.xrite.com/categories/portable-spectrophotometers/ci6x-family/ci64 (accessed May 08, 2020).
X-rite (Ci), Ci62L+RTL	R, Solid	NA, 8	d/8, Gas-filled tungsten, 400−700, 10	Ci62L+RTL. https://www.xrite.com/categories/portable-spectrophotometers/ci62lrtl (accessed May 08, 2020).
X-rite (Ci), Ci52	R, Solid	NA, 8	d/8, Gas-filled tungsten, 400−700, 10	Ci52. https://www.xrite.com/categories/portable-spectrophotometers/ci52 (accessed May 08, 2020).
X-rite (ERX), ERX130	R, Solid, Contactless, moving object	300, 90	Inline (0), −, 330−730, 1	ERX130. https://www.xrite.com/-/media/xrite/files/literature/misc/e/erx130_e_brochure_spectrophotometer_en.pdf (accessed May 08, 2020).
X-rite (ERX), ERX40	R, Semisolid, Pulp measurements	10	45c/0, −, 330−730, 1	ERX40. https://www.xrite.com/categories/inline-measurement/erx40 (accessed May 08, 2020).
X-rite (ERX), ERX30	R, Solid, Contactless	10	45c/0, −, 330−730, 1	ERX30. https://www.erx50.com/en/products/erx30# (accessed May 08, 2020).
X-rite (ERX), ERX145	R, Solid, Contactless	60, 30	45a/0, Xenon flash, 330−730, 1	ERX145. https://www.erx50.com/en/products/erx145# (accessed May 08, 2020).
X-rite (ERX), ERX56	R, Solid, Multiangle, Contactless, moving object, gloss measurement	10	15/15, 45/45, 60/60, −, 330−730, 1	ERX56. https://www.xrite.com/categories/inline-measurement/erx56 (accessed May 08, 2020).
X-rite (ERX), ERX50	R, Solid, Contactless, moving object	10, 12	45c/0, Xenon flash, 330−730, 1	ERX50. https://www.erx50.com/en/products/erx50# (accessed May 08, 2020).
X-rite (ERX), ERX55	T, Solid, Contactless, moving object	20, 12	Inline (0), Xenon flash, 330−730, 1	ERX55. https://www.xrite.com/-/media/xrite/files/literature/misc/e/erx55_e_brochure_spectrophotometer_transmission-haze_en.pdf (accessed May 08, 2020).
X-rite (eXact), eXact	R, Solid, Portable, filters M0, M1, M2, M3, Xp	NA, 1.5, 2, 4, 6	45c/0, Gas filled tungsten (illuminant type A) and UV LED, 400−700, 10	eXact. https://www.xrite.com/categories/portable-spectrophotometers/exact (accessed May 08, 2020).
X-rite (MA), MA-5 QC	R, Solid, Multiangle curved surface measurement	NA, 12	r45as15, r45as25, r45as45, r45as75, r45as110, −, 400−700, 10	MA-5 QC. https://www.xrite.com/categories/portable-spectrophotometers/ma-family/ma-5_qc (accessed May 08, 2020).
X-rite (MA), MA-T6	R, Solid, Mutiangle with sparkle measurement, 6 angle illumination 1 angle pickup	NA, Rectangle 9 × 12	15as-15, 15as15, 15as-30, 15as45,15as45,15as80, 15d, LED, 400−700, 10	MA-T6. https://www.xrite.com/-/media/xrite/files/literature/l10/l10-500_l10-599/l10-569_mat6_sellsheet/l10-569-ma-t6-sell-sheet-en.pdf (accessed May 08, 2020).
X-rite (MA), MA-T12	R, Solid, Mutiangle with sparkle measurement, 6 angle illumination 2 angle pickup	NA, Rectangle 9 × 12	15as-15, 15as15, 15as-30, 15as45,15as45,15as80, 15d, LED, 400−700, 10	MA-T12. https://www.xrite.com/-/media/xrite/files/literature/l10/l10-500_l10-599/l10-565_mat12_sellsheet/l10-565-ma-t12-sell-sheet-en.pdf (accessed May 08, 2020).
X-rite, RM400	R, Solid	NA, 8	45/0, Gas-filled tungsten, 400−700, 20	RM400. https://www.xrite.com/categories/portable-spectrophotometers/rm400 (accessed May 08, 2020).
X-rite, MatchRite iVue	R, Solid, Any shape, Contactless	38 and 6, 12	45/0, LED, 400−700, 10	MatchRite iVue. https://www.xrite.com/categories/benchtop-spectrophotometers/matchrite-ivue (accessed May 08, 2020).
X-rite, MetaVue VS3200	R, Solid, Contactless, Variable aperture	50, 2−12	45/0, LED, 400−700, 10	MetaVue VS3200. https://www.xrite.com/-/media/xrite/files/literature/l10/l10-500_l10-599/l10-586_metavue_vs3200_sell_sheet/l10-586-metavue-vs3200-sell-sheet-en.pdf (accessed May 08, 2020).
X-rite, VS450	R, Solid, Contactless, 45° gloss	38 and 6, 12	45/0, LED, 400−700, 10	VS450. https://www.xrite.com/-/media/xrite/files/manuals_and_userguides/v/vs450-500_vs450_operators_manual_en.pdf (accessed May 08, 2020).
X-rite (VeriColor), VeriColor Spectro	R, Solid, Not sensitive to incandescent, fluorescent, or sodium light of intensity 3000 lx, Moving object	100	30/0, 0/30, LED, 400−700, 10	VeriColor Spectro. https://www.xrite.com/categories/inline-measurement/vericolor-spectro (accessed May 08, 2020).
X-rite (VeriColor), VeriColor Solo	R, Solid, Not sensitive to incandescent, fluorescent, or sodium light of intensity 3000 lx, Moving object	100	30/0, 0/30, LED, 400−700, 10	VeriColor Solo. https://www.xrite.com/-/media/xrite/files/literature/l10/l10-200_l10-299/l10-248_vericolor_solo_sell_sgeet/l10-248_vericolorsolo_en.pdf (accessed May 08, 2020).
Agilent (Cary 3500), Cary 3500 UV−vis	T, Liquid	NA, NA	Inline (0), Xenon flash, 190−1100, 0.01	Cary 3500 UV−vis. https://www.agilent.com/en/products/uv-vis-uv-vis-nir/uv-vis-uv-vis-nir-systems/cary-3500-uv-vis#specifications (accessed May 08, 2020).

https://doi.org/10.1021/acsomega.2c08252
ACS Omega 2023, 8, 23257−23270

Table 2. continued

Mfr (Inst Family), Spectrometer Name	Type, Sample Type, Specialty	Range (mm), Measured Spot Diameter (R) or Optical Path Length (T) (mm)	Geometry, Light Source, Spectrum Range (nm), Sampling Frequency (nm)	Source
Agilent (Cary 3500), Cary 3500 Multicell UV−vis	T, Liquid, 8 cells with combinations of samples and references	NA, NA	Inline (0), Xenon flash, 190−1100, 0.01	Cary 3500 Multicell UV−vis. https://www.agilent.com/en/products/uv-vis-uv-vis-nir/uv-vis-uv-vis-nir-systems/cary-3500-uv-vis#specifications (accessed May 08, 2020).
Agilent (Cary 3500), Cary 3500 Compact UV−vis	T, Liquid, 2 cells, One sample and one reference	NA, NA	Inline (0), Xenon flash, 190−1100, 0.01	Cary 3500 Compact UV−vis. https://www.agilent.com/en/products/uv-vis-uv-vis-nir/uv-vis-uv-vis-nir-systems/cary-3500-uv-vis#specifications (accessed May 08, 2020).
BMG Labtech, CLARIOstar Plus	R/T, Liquid, 50 plates, Microplate reader	NA, NA	Inline (0), Xenon flash, 220−1000, 1, 2, 5, 10	CLARIOstar Plus. https://www.bmglabtech.com/clariostar-plus/ (accessed May 08, 2020).
Micro-Epsilon (colorControl), colorCONTROL ACS7000 ACS1	R, Solid/Liquid, Contactless, Speed 2 kHz, Moving object	50, 38 and 9	30/0, 45/0, LED, 390−780, 5	colorCONTROL ACS7000 ACS1. https://www.micro-epsilon.com/color/colorCONTROL_ACS/?sLang=us&gclid=EAIaIQobChMIj7jX2J2K6QIVJ_fjBx3AfAl2EAMYAyAAEgLe3_D_BwE (accessed May 08, 2020).
Micro-Epsilon (colorControl), colorCONTROL ACS7000 ACS2	R, Solid/liquid, Contactless, Speed 2 kHz, Moving object	28 and 5, 9, 3	45c/0, LED, 390−780, 5	colorCONTROL ACS7000 ACS2. https://www.micro-epsilon.com/color/colorCONTROL_ACS/?sLang=us&gclid=EAIaIQobChMIj7jX2J2K6QIVJ_fjBx3AfAl2EAMYAyAAEgLe3_D_BwE (accessed May 08, 2020).
Micro-Epsilon (colorControl), colorCONTROL ACS7000 ACS3	T, Solid/liquid, Contactless, Speed 2 kHz, Moving object	10−300 and 5, 9, 15	Inline (0), LED, l390−780, 5	colorCONTROL ACS7000 ACS3. https://www.micro-epsilon.com/color/colorCONTROL_ACS/?sLang=us&gclid=EAIaIQobChMIj7jX2J2K6QIVJ_fjBx3AfAl2EAMYAyAAEgLe3_D_BwE (accessed May 08, 2020).
Micro-Epsilon (colorSensor), colorSENSOR CFO100/CFO200	R/T, Solid/liquid, Colorimeter, Contactless, Speed 10 kHz, Moving object	2−100, 0.6−20	Inline (0), LED, NA, NA	colorSENSOR CFO100/CFO200. https://www.micro-epsilon.com/color/colorSENSOR-CFO/ (accessed May 08, 2020).
Antas technology corporation, Probe	R/T, Solid/liquid, Contactless	25, 5	Inline (0), Halogen, 350−850, 1	Probe. http://www.antas-tech.com/m/404-1279-19927.php?Lang=zh-tw (accessed May 08, 2020).
Caldera (Total Color), Total Color qb	R/T, Solid, Automated multipatch, D50	NA, 2, 6, 8	−, LED, −, 2	Total Color qb. https://www.caldera.com/wp-content/uploads/2018/11/TotalColor-QB_Features-Technology-Content.pdf (accessed May 08, 2020).
Caldera (Total Color), Total Color	R, Solid, Automated multipatch, D50	NA, 2, 6, 8	−, LED, −, 2	Total Color. https://www.caldera.com/wp-content/uploads/2018/11/Datasheet_TOTALCOLOR_2017.pdf (accessed May 08, 2020).
Caldera, Colorpad	R, Solid, Manual, D50	NA, 6	−, LED, −, −	Colorpad. https://www.caldera.com/wp-content/uploads/2018/11/Datasheet_ColorPad.pdf (accessed May 08, 2020).
Testronix, TP810	R, Solid	NA	d/8, LED, 400−700, 10	TP810. http://www.testronixinstruments.com/blog/spectrophotometers-to-measure-color-consistency-of-plastics/ (accessed May 08, 2020).
Testronix, TP800	R, Solid/liquid, Designed for plastic	NA	45/0, d, LED, 400−700, 10	TP800. http://www.testronixinstruments.com/portable-spectrophotometer/ (accessed May 08, 2020).
Testronix, TP310	R, Solid/liquid, Designed for plastic	NA, 4, 8	8/d, D65, D50A, −, 10	TP310. http://www.testronixinstruments.com/portable-color-device/ (accessed May 08, 2020).
Testronix, TP110	R, Solid/liquid, Designed for plastic	NA, 4	8/d, D65, −, 10	TP110. http://www.testronixinstruments.com/precision-color-device/ (accessed May 08, 2020).
LIAD, SpectroSave	R/T, Solid, Contactless, 6 fiber optic sensors	NA, 9	Inline (0), Tungsten halogen, −, 12	SpectroSave. https://liad.co.il/wp-content/uploads/2020/01/SpectroSave-Brochure-English.pdf (accessed May 08, 2020).
Datacolor (Datacolor 800), Datacolor 800	R, Solid, Dual beam, Horizontal design, UV filters 400, 420, 460	NA, 2.5, 5, 16, 26	d/8, Pulsed xenon filtered to D65, 360−700, 10	Datacolor 800/800v/850. https://www.datacolor.com/wp-content/uploads/2016/08/DC800_Specsheet_EN_web.pdf (accessed May 08, 2020).
Datacolor (Datacolor 800), Datacolor 800v	R, Solid, Dual beam, Vertical design, UV filters 400, 420, 460	NA, 2.5, 5, 16, 26	d/8, Pulsed xenon filtered to D65, 360−700, 10	Datacolor 800/800v/850. https://www.datacolor.com/wp-content/uploads/2016/08/DC800_Specsheet_EN_web.pdf (accessed May 08, 2020).
Datacolor (Datacolor 800), Datacolor 850	T, Solid, Dual beam, Horizontal design, UV filters 400, 420, 460	NA, 2.5, 5, 16, 26	d/8, Pulsed xenon filtered to D65, 360−700, 10	Datacolor 800/800v/850. https://www.datacolor.com/wp-content/uploads/2016/08/DC800_Specsheet_EN_web.pdf (accessed May 08, 2020).
Datacolor (Datacolor 500), Datacolor 500	R, Solid, Dual beam, No UV filter	NA, 2.5, 5, 16, 26	d/8, Pulsed xenon filtered to D65, 360−700, 10	Datacolor 500/500UV/550. https://www.datacolor.com/wp-content/uploads/2016/08/DC500-specsheet-EN_web.pdf (accessed May 08, 2020).

https://doi.org/10.1021/acsomega.2c08252
ACS Omega 2023, 8, 23257−23270

Table 2. continued

Mfr (Inst Family), Spectrometer Name	Type, Sample Type, Specialty	Range (mm), Measured Spot Diameter (*R*) or Optical Path Length (*T*) (mm)	Geometry, Light Source, Spectrum Range (nm), Sampling Frequency (nm)	Source
Datacolor (Datacolor 500), Datacolor 500UV	R, Solid, Dual beam, UV filters 400, 420, 460	NA, 2.5, 5, 16, 26	d/8, Pulsed xenon filtered to D65, 360−700, 10	Datacolor 500/500UV/550. https://www.datacolor.com/wp-content/uploads/2016/08/DC500-specsheet-EN_web.pdf (accessed May 08, 2020).
Datacolor (Datacolor 500), Datacolor 550	T, Solid, Dual beam, UV filters 400, 420, 460	NA, 2.5, 5, 16, 26	d/8, Pulsed xenon filtered to D65, 360−700, 10	Datacolor 500/500UV/550. https://www.datacolor.com/wp-content/uploads/2016/08/DC500-specsheet-EN_web.pdf (accessed May 08, 2020).
Datacolor (Datacolor 200), Datacolor 200R	R, Solid	NA, 6.5, 9 or 22	d/8, Pulsed xenon filtered to D65, 400−700, 10	Datacolor 200R. https://www.datacolor.com/wp-content/uploads/2016/08/DC200R_Specsheet_EN_web.pdf (accessed May 08, 2020).
Datacolor (Datacolor 200), Datacolor 200M	R, Solid, Dual beam	NA, 6.5, 9 or 22	d/8, Pulsed xenon filtered to D65, 400−700, 10	Datacolor 200M. https://www.datacolor.com/wp-content/uploads/2016/08/DC200M-specsheet-en.pdf (accessed May 08, 2020).
Datacolor (Datacolor 45), Datacolor 45G	R, Solid, Built-in 60° gloss	NA, 8	45c/0, LED, 400−700, 10	Datacolor 45G. https://www.datacolor.com/wp-content/uploads/2016/08/45G-product-spec-sheet-EN-1.pdf (accessed May 08, 2020).
Datacolor (Datacolor 45), Datacolor 45S	R, Solid	NA, 8	45c/0, LED400−700, 10	Datacolor 45S. https://www.datacolor.com/wp-content/uploads/2016/08/45S-product-spec-sheet-EN-1.pdf (accessed May 08, 2020).
Datacolor, Datacolor 45IR	R, Solid, Good for printed security inks	NA, 3	0/45x, −, 380−1100, 10	Datacolor 45IR. https://www.datacolor.com/business-solutions/product-overview/datacolor-45ir/ (accessed May 08, 2020).
Datacolor, Datacolor 20D	R, Solid	NA, 6.5	d/8, Pulsed xenon, 400−700, 10	Datacolor 20D. https://www.datacolor.com/wp-content/uploads/2016/08/DC20D_Specsheet_EN_web.pdf (accessed May 08, 2020).
Datacolor, Datacolor Check 3	R, Solid	NA, 2.5, 6.5, 11	d/8, Pulsed xenon, 360−700, 10	Datacolor Check 3. https://www.datacolor.com/wp-content/uploads/2016/08/Check3_Specsheet_EN_web.pdf (accessed May 08, 2020).
Datacolor, Datacolor Spectravision	R, Solid, Horizontal design, UV filters 400, 420, 460, Barium-coated integrating sphere	NA, Square size 22.7	de/8, di/8, Pulsed xenon filtered to D65, 400−700, 10	Datacolor Spectravision. https://www.datacolor.com/wp-content/uploads/2018/05/spectravision-brochure-digital-EN-1.pdf (accessed May 08, 2020).
Datacolor, Datacolor ELREPHO	R, Solid, Dual beam	NA, 2.5, 5, 30	d/0, Pulsed xenon filtered to D65, 360−700, 10	Datacolor ELREPHO. https://www.datacolor.com/business-solutions/product-overview/datacolor-elrepho/ (accessed May 08, 2020).
BYK (Spectro 2 guide color control), spectro-guide 45/0 gloss	R, Solid, 60° gloss	NA, 11	45/0, LED, 400−700, 10	spectro-guide 45/0 gloss. https://www.byk-instruments.com/us/en/Color/spectro2guide-Color-Control/Color-control-for-basic-tasks/spectro-guide-45-0-gloss/p/6801 (accessed May 08, 2020).
BYK (Spectro 2 guide color control), spectro-guide 45/0 gloss S	R, Solid, Improved technical performance for 60° gloss < 10 GU	NA, 11	45/0, LED, 400−700, 10	spectro-guide 45/0 gloss S. https://www.byk-instruments.com/us/en/Color/spectro2guide-Color-Control/Color-control-for-basic-tasks/spectro-guide-45-0-gloss-S/p/6802 (accessed May 08, 2020).
BYK (Spectro 2 guide color control), spectro-guide sphere gloss	R, Solid, 60° gloss	NA, 11	di/8, LED, 400−700, 10	spectro-guide sphere gloss. https://www.byk-instruments.com/us/en/Color/spectro2guide-Color-Control/Color-control-for-basic-tasks/spectro-guide-sphere-gloss/p/6834 (accessed May 08, 2020).
BYK (Spectro 2 guide color control), spectro-guide sphere gloss S	R, Solid, Improved technical performance for 60° gloss < 10 GU	NA, 11	di/8, LED, 400−700, 10	spectro-guide sphere gloss S. https://www.byk-instruments.com/us/en/Color/spectro2guide-Color-Control/Color-control-for-basic-tasks/spectro-guide-sphere-gloss-S/p/6836 (accessed May 08, 2020).
BYK (Spectro 2 guide color control), spectro2go 45/0	R, Solid, 60° gloss	NA, 8	45c/0, LED, 340−760, 10	spectro2go 45/0. https://www.byk-instruments.com/us/en/Color/spectro2guide-Color-Control/Color-control-with-digital-standards/spectro2go-45-0/p/7085 (accessed May 08, 2020).
BYK (Spectro 2 guide color control), spectro2go d/8	R, Solid, 60° gloss	NA, 8	de/8, di/8, LED, 340−760, 10	spectro2go d/8. https://www.byk-instruments.com/us/en/Color/spectro2guide-Color-Control/Color-control-with-digital-standards/spectro2go-d-8/p/7086 (accessed May 08, 2020).
BYK (Spectro 2 guide color control), spectro2guide d/8	R, Solid, 60° gloss and fluorescence	NA, 8	d/8, LED, 340−760, 10	spectro2guide d/8. https://www.byk-instruments.com/us/en/Color/spectro2guide-Color-Control/Color-control-of-fluorescent-and-non-fluorescent-samples/spectro2guide-d-8%C2%A0%C2%A0%C2%A0%C2%A0%C2%A0%C2%A0%C2%A0%C2%A0%C2%A0%C2%A0%C2%A0%C2%A0%C2%A0%C2%A0%C2%A0%C2%A0%C2%A0%C2%A0%C2%A0/p/7070 (accessed May 08, 2020).

https://doi.org/10.1021/acsomega.2c08252
ACS Omega 2023, 8, 23257−23270

Table 2. continued

Mfr (Inst Family), Spectrometer Name	Type, Sample Type, Specialty	Range (mm), Measured Spot Diameter (*R*) or Optical Path Length (*T*) (mm)	Geometry, Light Source, Spectrum Range (nm), Sampling Frequency (nm)	Source
BYK, (Spectro 2 guide color control), spectro2guide 45/0	R, Solid, 60° gloss and fluorescence	NA, 8	45c/0, LED, 340−760, 10	spectro2guide 45/0. https://www.byk-instruments.com/us/en/Color/spectro2guide-Color-Control/Color-control-of-fluorescent-and-non-fluorescent-samples/spectro2guide-45-0%C2%A0/p/7075 (accessed May 08, 2020).
BYK (Spectro 2 guide color control), spectro2guide Pro 45/0	R, Solid, Designed for deep black measurement, 60° gloss and fluorescence	NA, 8	45c/0, LED, 340−760, 10	spectro2guide Pro 45/0. https://www.byk-instruments.com/us/en/Color/spectro2guide-Color-Control/Jetness-control-for-deepest-black/spectro2guide-Pro-45-0/p/7087 (accessed May 08, 2020).
BYK (Spectro 2 guide color control), color-guide 45/0, glass sealed	R, Solid, Designed for powders	NA, 20 (glass sealed)	45/0, LED, 400−700, 20	color-guide 45/0, glass sealed. https://www.byk-instruments.com/us/en/Color/spectro2guide-Color-Control/Color-meter-with-4-mm-or-glass-sealed-opening/color-guide-45-0%2C-glass-sealed/p/6692 (accessed May 08, 2020).
BYK (Spectro 2 guide color control), color-guide 45/0, 4 mm	R, Solid, Designed for small parts	NA, 4	45/0, LED, 400−700, 20	color-guide 45/0, 4 mm. https://www.byk-instruments.com/us/en/Color/spectro2guide-Color-Control/Color-meter-with-4-mm-or-glass-sealed-opening/color-guide-45-0%2C-4mm/p/6807 (accessed May 08, 2020).
BYK (BYK-mac i MetallicColor), BYK-mac i 23 mm	R, Solid, Perpendicular viewing	NA, 23	as −15, 15, 25, 45, 75, 110, LED, 400−700, 10	BYK-mac i 23 mm. https://www.byk-instruments.com/us/en/Color/BYK-mac-i-MetallicColor/BYK-mac-i-23-mm/c/p-346 (accessed May 08, 2020).
BYK, (BYK-mac i MetallicColor), BYK-mac i Sensor 23 mm	R, Solid, Perpendicular viewing	NA, 23	as −15, 15, 25, 45, 75, 110, LED, 400−700, 10	BYK-mac i Sensor 23 mm. https://www.byk-instruments.com/us/en/Color/BYK-mac-i-MetallicColor/BYK-mac-i-23-mm/BYK-mac-i-Sensor-23-mm/p/7031 (accessed May 08, 2020).
BYK (BYK-mac i MetallicColor), BYK-mac i 12 mm	R, Solid, Perpendicular viewing	NA, 12	as −15, 15, 25, 45, 75, 110, LED, 400−700, 10	BYK-mac i 12 mm. https://www.byk-instruments.com/us/en/Color/BYK-mac-i-MetallicColor/BYK-mac-i-12-mm/BYK-mac-i-12-mm/p/7034 (accessed May 08, 2020).
BYK (BYK-mac i MetallicColor), BYK-mac i Sensor 12 mm	R, Solid, Perpendicular viewing	NA, 12	as −15, 15, 25, 45, 75, 110, LED, 400−700, 10	BYK-mac i Sensor 12 mm. https://www.byk-instruments.com/us/en/Color/BYK-mac-i-MetallicColor/BYK-mac-i-12-mm/BYK-mac-i-Sensor-12-mm/p/7035 (accessed May 08, 2020).
BYK (BYK-mac i MetallicColor), BYK-mac i COLOR	R, Solid, Perpendicular viewing	NA, 23	as −15, 15, 25, 45, 75, 110, LED, 400−700, 10	BYK-mac i COLOR. https://www.byk-instruments.com/us/en/Color/BYK-mac-i-MetallicColor/BYK-mac-i-COLOR/BYK-mac-i-COLOR/p/7032 (accessed May 08, 2020).
BYK (BYK-mac i MetallicColor), BYK-mac i COLOR Sensor	R, Solid, Perpendicular viewing	NA, 21	as −15, 15, 25, 45, 75, 110, LED, 400−700, 10	BYK-mac i COLOR Sensor. https://www.byk-instruments.com/us/en/Color/BYK-mac-i-MetallicColor/BYK-mac-i-COLOR/BYK-mac-i-COLOR-Sensor/p/7033 (accessed May 08, 2020).
BYK (BYK-mac i MetallicColor), BYK-mac i ROBOTIC	R, Solid, Robotic measurements, Perpendicular viewing	NA, Rectangle 87x23	as −15, 15, 25, 45, 75, 110, LED, 400−700, 10	BYK-mac i ROBOTIC. https://www.byk-instruments.com/us/en/Color/BYK-mac-i-MetallicColor/BYK-mac-i-ROBOTIC/BYK-mac-i-ROBOTIC/p/7036 (accessed May 08, 2020).
BYK (Gardner Color Liquids), LCM IV	T, Liquid, Only 2° observer	NA, 10, 11, 50	Inline (0), Tungsten halogen, 380−720, 10	LCM IV. https://www.byk-instruments.com/us/en/Color/Gardner-Color-Liquids/LCM-IV/LCM-IV/p/9561 (accessed May 08, 2020).
BYK (Gardner Color Liquids), LCS IV	T, Liquid	NA, 10, 11	Inline (0), Tungsten halogen, 320−1100, 1	LCM IV. https://www.byk-instruments.com/us/en/Color/Gardner-Color-Liquids/LCM-IV/LCM-IV/p/9561 (accessed May 08, 2020).
BYK (spectro2profiler Color & 3D Topography), spectro2profiler	R, Solid, 3D topography, 60° gloss	NA, 25	45c/0, LED, 400−700, 10	spectro2profiler. https://www.byk-instruments.com/us/en/Color/spectro2profiler-Color-%26-3D-Topography/Color-and-3D-Topography-Analyzer/spectro2profiler/p/7300 (accessed May 08, 2020).
Hack, DR1900	T, Liquid, Portable, Rotation of sample	NA, Sq.: 10, 25, circ.: 13, 16	Inline (0), Xenon flash, 340−800, 1	DR1900. https://www.hach.com/asset-get.download.jsa?id=21410202552 (accessed May 08, 2020).
Hack, DR3900	T, Liquid, Rotation of sample	NA, Sq.: 10, 25, 50, circ.: 13, 16	Inline (0), Halogen, 320−1100, 1	DR3900. https://www.hach.com/asset-get.download.jsa?id=7639984457 (accessed May 08, 2020).
Hack, DR6000	T, Liquid, Rotation of sample	NA, Sq.: 10, 25, 50, circ.: 13, 16	Inline (0), Deuterium, Halogen, 190−1100, 0.1	DR6000. https://www.hach.com/asset-get.download.jsa?id=12166310603 (accessed May 08, 2020).
Jasco (V-700), V-730	T, Liquid, Double beam	NA, 10	Inline (0), d, Deuterium, Halogen, 190−1100, 1	Jasco V-700. https://jascoinc.com/wp-content/uploads/2018/05/V-700-Catalog.pdf (accessed May 08, 2020).

https://doi.org/10.1021/acsomega.2c08252
ACS Omega 2023, 8, 23257−23270

Table 2. continued

Mfr (Inst Family), Spectrometer Name	Type, Sample Type, Specialty	Range (mm), Measured Spot Diameter (R) or Optical Path Length (T) (mm)	Geometry, Light Source, Spectrum Range (nm), Sampling Frequency (nm)	Source
Jasco (V-700), V-750	T, Liquid, Double beam	NA, 10	Inline (0), d, Deuterium, Halogen, 190−900, 0.1 to 10 with selective bandwidths	Jasco V-700. https://jascoinc.com/wp-content/uploads/2018/05/V-700-Catalog.pdf (accessed May 08, 2020).
Jasco (V-700), V-760	T, Liquid, Double beam, double monochromator	NA, 10	Inline (0), d, Deuterium, Halogen, 190−900, 0.1 to 10 with selective bandwidths	Jasco V-700. https://jascoinc.com/wp-content/uploads/2018/05/V-700-Catalog.pdf (accessed May 08, 2020).
Jasco (V-700), V-770	T, Liquid, Double beam	NA, 10	Inline (0), d, Deuterium, Halogen, 190−3200, 0.1 to 10 with selective bandwidths	Jasco V-700. https://jascoinc.com/wp-content/uploads/2018/05/V-700-Catalog.pdf (accessed May 08, 2020).
Jasco (V-700), V-780	T, Liquid, Double beam	NA, 10	Inline (0), d, Deuterium, Halogen, 190−1600, 0.1 to 10 with selective bandwidths	Jasco V-700. https://jascoinc.com/wp-content/uploads/2018/05/V-700-Catalog.pdf (accessed May 08, 2020).
Jasco (MV-3000), MV-3100	R/T, Solid/Liquid, Portable and for thin films as well as liquids	NA, 10	Inline (0), Deuterium, Halogen, 200−800, 5	Jasco MV-3000. https://jascoinc.com/products/spectroscopy/uv-visible-nir-spectrophotometers/models/mv-3000-series-portable-uv-visible-nir-spectrophotometer/ (accessed May 08, 2020).
Jasco (MV-3000), MV-3150	R/T, Solid/liquid, Portable and for thin films as well as liquids	NA, 10	Inline (0), Deuterium, Halogen, 200−800, 5	Jasco MV-3000. https://jascoinc.com/products/spectroscopy/uv-visible-nir-spectrophotometers/models/mv-3000-series-portable-uv-visible-nir-spectrophotometer/ (accessed May 08, 2020).
Jasco (MV-3000), MV-3200	R/T, Solid/liquid, Portable and for thin films as well as liquids	NA, 10	Inline (0), Deuterium, Halogen, 350−900, 5	Jasco MV-3000. https://jascoinc.com/products/spectroscopy/uv-visible-nir-spectrophotometers/models/mv-3000-series-portable-uv-visible-nir-spectrophotometer/ (accessed May 08, 2020).
Jasco (MV-3000), MV-3250	R/T, Solid/Liquid, Portable and for thin films as well as liquids	NA, 10	Inline (0), Deuterium, Halogen, 350−900, 5	Jasco MV-3000. https://jascoinc.com/products/spectroscopy/uv-visible-nir-spectrophotometers/models/mv-3000-series-portable-uv-visible-nir-spectrophotometer/ (accessed May 08, 2020).
Perkin-Elmer (LAMBDA), LAMBDA XLS/XLS+	T, Liquid, Split beam	NA, 10, 20, 40	Inline (0), Xenon flash, 190−1100, 5, 3	LAMBDA XLS/XLS+. https://www.perkinelmer.com/lab-solutions/resources/docs/BRO_LAMBDAXLSandXLSPlus.pdf (accessed May 08, 2020).
Perkin-Elmer (LAMBDA), LAMBDA BIO/BIO+	T, Liquid, Split beam, low volume cuvettes	NA, 10	Inline (0), Xenon flash, 190−1100, 5, 3	LAMBDA BIO/BIO+. https://www.perkinelmer.com/lab-solutions/resources/docs/DTS_Personal-UV-Vis-Spectrophotomers-008106C_01.pdf (accessed May 08, 2020).
Konica Minolta, CM-26dG/26d	R, Solid, 60° gloss − 26dG	NA, 8, 3	de/8, di/8, Two pulsed xenon lamps, 360−740, 10	CM-26dG/26d/25d. https://sensing.konicaminolta.us/wp-content/uploads/cm26dg_catalog_eng-7i3s4i056r.pdf (accessed May 08, 2020).
Konica Minolta, CM-25d	R, Solid, 60° gloss	NA, 8	de/8, di/8, Pulsed xenon lamp, 400−700, 10	CM-26dG/26d/25d. https://sensing.konicaminolta.us/wp-content/uploads/cm26dg_catalog_eng-7i3s4i056r.pdf (accessed May 08, 2020).
Konica Minolta, CM-25cG	R, Solid	NA, 8, 3	45c/0, Pulsed xenon lamp, 360−740, 10	CM-25cG. https://sensing.konicaminolta.us/wp-content/uploads/cm-25cg_catalog-n7fq7l24a9.pdf (accessed May 08, 2020).
Konica Minolta, CM-700d/600d	R, Solid	NA, 8, 11, 3, 6	de/8, di/8, Pulsed xenon lamp with UV filter, 400−700, 10	CM—700d/600d. https://sensing.konicaminolta.us/wp-content/uploads/cm-700d_600d_catalog-5v0252564m.pdf (accessed May 08, 2020).
Konica Minolta, CM-M6	R, Solid, Multiangle with dual path technology	NA, 6, 12	45as-15, 45as15, 45as25, 45as45, 45as75, 45as110, LED, 400−700, 10	CM-M6. https://sensing.konicaminolta.us/wp-content/uploads/cm-m6_catalog-2n9p789453.pdf (accessed May 08, 2020).
Konica Minolta, CM-3600A/3610A	R/T, Solid/liquid, Particle, continuous surface and liquid	NA, R: 4, 8, 25.4, T: 17(2, 10, 20)	de/8, di/8, Four pulsed xenon lamps, 360−740, 10	CM-3600A/3610A. https://sensing.konicaminolta.us/wp-content/uploads/cm-3600a_3610a_catalog-c1849x75cc.pdf (accessed May 08, 2020).
Konica Minolta, CM-3700A	R/T, Solid/Liquid, Particle, continuous surface and liquid	NA, R: 3 × 4, 8, 25.4, T: 20(2, 10, 20)	de/8, di/8, Pulsed xenon arc lamp, 360−740, 10	CM-3700A. https://sensing.konicaminolta.us/wp-content/uploads/cm3700a_catalog-59b1s31495.pdf (accessed May 08, 2020).
Konica Minolta, CM-5	R/T, Solid/Liquid, Particle, continuous surface and liquid	NA, R: 30, 8, 3, T: 20 (2, 10, 20)	de/8, di/8, Pulsed xenon arc lamp, 360−740, 10	CM-5. https://sensing.konicaminolta.us/wp-content/uploads/cm-5_catalog-3767wp28c1.pdf (accessed May 08, 2020).
Konica Minolta, LCS IV	T, Liquid	NA, 10, 11	Inline (0), Tungsten halogen, 380−720, 10	LCS IV. https://sensing.konicaminolta.us/wp-content/uploads/catalogpageslcsiv-0371651811.pdf (accessed May 08, 2020).

https://doi.org/10.1021/acsomega.2c08252
ACS Omega 2023, 8, 23257−23270

Table 2. continued

Mfr (Inst Family), Spectrometer Name	Type, Sample Type, Specialty	Range (mm), Measured Spot Diameter (*R*) or Optical Path Length (*T*) (mm)	Geometry, Light Source, Spectrum Range (nm), Sampling Frequency (nm)	Source
Technidyne (ColorTouch), PROFILE/Plus Color Touch	R, Solid, Other optical tests for paper	NA	D, Pulsed xenon, −, −	Technidyne PROFILE/Plus Color Touch. https://ee19b3b1-0164-4917-aba4-fc32de608c36.filesusr.com/ugd/1cbb1e_2283193b66f745a2946caa984866f023.pdf (accessed May 08, 2020).
Technidyne (ColorTouch), ColorTouch X	R, Solid, Dual beam, Other optical tests for paper	NA, 30	d/0, Pulsed xenon, 360−780, 1, 5, 10, 20	Technidyne ColorTouch X. https://ee19b3b1-0164-4917-aba4-fc32de608c36.filesusr.com/ugd/857e28_9ad0b019b499457d8e9ee9adb84283c4.pdf (accessed May 08, 2020).
Technidyne (ColorTouch), ColorTouch PC	R, Solid, Dual beam, Other optical tests for paper	NA, 34, 10, 18	d/0, Pulsed xenon, 400−700, 5, 10, 20	Technidyne ColorTouch PC. https://ee19b3b1-0164-4917-aba4-fc32de608c36.filesusr.com/ugd/1cbb1e_b98dc9c9fb85497b824cefccce9e372e.pdf (accessed May 08, 2020).

[a]T = transmittance, R = reflectance, NA = not applicable, − = no information.

off-line. The precision of the measurement is typically high, but the processing time can be long. Also, any deviation in color detected in the sample applies to the whole batch of processed material. There is almost no ability to take corrective action. The at-line method is a parallel system to the production. The samples are automatically gathered from the production line and sent to the measurement sites. The in-line method is a live measurement system, or it is active at a predetermined sampling rate. This is an automatic method where the color-measuring probe is integrated with the system.

■ INDUSTRIAL PRACTICES AND STANDARDS FOR THE COLOR MEASUREMENT OF PLASTICS

Industrial applications of color measurements are based on the standards developed by organizations including ASTM, ISO, and CIE. The principles and calculations of color measurements are defined by CIE. Their methods and standards are further applied in ASTM and ISO standards. The following set of important factors from various standards can be used to create a guideline for color measurements in plastics:

The Association of Plastic Recyclers suggests the average of 5 measurement of samples for reporting.[59]

Colors are reported in CIELAB values for D65/10° condition.[59−61]

Instrument, standards, temperature, and humidity should be reported for the color measurements. Recommended reproducibility of results should be 95%.[62]

ASTM suggests that the measurement of plastic pellets needs to be done by filling a clear glass cell of minimum depth of 50 mm.[60]

The measurement area is recommended to be 25 mm for d/0 or 0/d spectrophotometers while 31−52 mm for 45/0 spectrophotometers.[60]

Color differences formulas for ΔE_{ab} or CIEDE2000 should be used from ASTM D2244.[63]

If a color difference is measured, the product standard should be used as a reference. The compared product geometries, spectral response, and measurement areas should be similar.[62]

For uniplanar geometry of measurements, a second reading is required by rotating the sample by 90° to consider the directionality of the sample.[62] This can be ignored for the nondirectional specimen.

The colors of transparent liquid samples should be measured in cuvettes of 20−150 mm path length.[61,64] On the other hand, Gardner color comparison method uses the path length of 10.65 mm with illuminant C.[65]

■ CURRENTLY AVAILABLE SPECTROPHOTOMETERS

Spectrophotometers are manufactured based on market needs, so that different spectrophotometers can be designed to serve specific purposes. Table 2 provides a list of various spectrophotometers, which may serve to measure colors of plastic particles, pellets, films or plaques, and suspended particles in liquids. The list provides the spectral range of the instrument, geometry, and special features of the instrument that directly affect the nature of the material being measured.

■ CONCLUSIONS

The color is one of the most complex multivariable characteristics of any material or product. This review summarizes the challenges and the approaches to their solutions. Measuring the colors of materials in different physical states can lead to different CIELAB values for color. Color correction factors need to be included in the measured values if the standard color specimen seems to deviate from the required spectral response. Color standards can be used to maximize the compatibility of the readings. Spectrophotometers with a broad range of capabilities can be used for spectral absorbance measurements, and the data can be converted to the CIELAB space. However, the spectral sensitivity and the geometry of the instrument should be considered. Diffuse geometry is considered to be suitable to reduce the effects of directionality of the material. However, multiple geometries can be used to have a better understanding of the color and appearance of a given object. Future developments in this field are likely to include the application of machine-learning methods for massive data processing and comparative analysis.

■ AUTHOR INFORMATION

Corresponding Author

Lokendra Pal − *Department of Forest Biomaterials, North Carolina State University, Raleigh, North Carolina 27695, United States;* orcid.org/0000-0001-5236-9983; Email: lpal@ncsu.edu

https://doi.org/10.1021/acsomega.2c08252
ACS Omega 2023, 8, 23257−23270

Authors

Sachin Agate − *Department of Forest Biomaterials, North Carolina State University, Raleigh, North Carolina 27695, United States*

Austin Williams − *Department of Chemical & Biomolecular Engineering, North Carolina State University, Raleigh, North Carolina 27695, United States;* orcid.org/0000-0003-4080-5164

Joseph Dougherty − *Eastman Chemical Company, Kingsport, Tennessee 37660, United States*

Orlin D. Velev − *Department of Chemical & Biomolecular Engineering, North Carolina State University, Raleigh, North Carolina 27695, United States;* orcid.org/0000-0003-0473-8056

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.2c08252

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This research was supported by Eastman Chemical Company (Project ID EMN-19-F-S-04).

■ REFERENCES

(1) Hu, J.; Chen, S. A review of actively moving polymers in textile applications. *Journal of Materials Chemistry* **2010**, *20* (17), 3346−3355.

(2) Bunsell, A. R., Fibers with High Modulus. In *Encyclopedia of Materials: Science and Technology*; Buschow, K. H. J., Cahn, R. W., Flemings, M. C., Ilschner, B., Kramer, E. J., Mahajan, S., Veyssière, P., Eds.; Elsevier: Oxford, 2001; pp 3151−3157. DOI: 10.1016/B0-08-043152-6/00560-X.

(3) Zou, Y.; Hsieh, J. S.; Mehnert, E.; Kokoszka, J. The study of PET recyclable polymers as paper coatings. *Progress in Organic Coatings* **2007**, *60* (2), 127−131.

(4) Auras, R. A.; Singh, S. P.; Singh, J. J. Evaluation of oriented poly(lactide) polymers vs. existing PET and oriented PS for fresh food service containers. *Packaging Technology and Science* **2005**, *18* (4), 207−216.

(5) Sapuan, S. M., Chapter 3 - Composite Materials. In *Composite Materials*; Sapuan, S. M., Ed.; Butterworth-Heinemann: Boston, 2017; pp 57−93. DOI: 10.1016/B978-0-12-802507-9.00003-9.

(6) Mason, W. R. Starch Use in Foods. In *Starch: Chemistry and Technology*, 3rd ed.; Elsevier, Inc., 2009; pp 745−795.

(7) Rosato, D. V.; Rosato, D. V.; Rosato, M. V. 5 - EXTRUSION. In *Plastic Product Material and Process Selection Handbook*; Rosato, D. V., Rosato, D. V., Rosato, M. V., Eds.; Elsevier: Oxford, 2004; pp 227−281. DOI: 10.1016/B978-185617431-2/50008-6.

(8) *Color and Appearance Measurement in Plastic Industry*; Konica Minolta, 2019.

(9) Phillips, K. Going Green with Color Technology: Variation in Plastics Makes Sorting Recyclables Easy. https://www.hunterlab.com/blog/going-green-with-color-technology-variation-in-plastics-makes-sorting-recyclables-easy/ (accessed March 10, 2023).

(10) Pinna, B.; Porcheddu, D.; Deiana, K. Illusion and Illusoriness of Color and Coloration. *Journal of Imaging* **2018**, *4* (2), 30.

(11) Bakshi, A.; Ghosh, K., A Neural Model of Attention and Feedback for Computing Perceived Brightness in Vision. In *Handbook of Neural Computation*; Elsevier, 2017; pp 487−513. DOI: 10.1016/b978-0-12-811318-9.00026-0.

(12) Schmidt, B. P.; Boehm, A. E.; Tuten, W. S.; Roorda, A. Spatial summation of individual cones in human color vision. *PLoS One* **2019**, *14* (7), No. e0211397.

(13) Roorda, A.; Williams, D. R. The arrangement of the three cone classes in the living human eye. *Nature* **1999**, *397* (6719), 520−2.

(14) Molday, R. S.; Moritz, O. L. Photoreceptors at a glance. *Journal of Cell Science* **2015**, *128* (22), 4039−4045.

(15) Müeller, H. F. O., Daylighting. In *Sustainability, Energy and Architecture: Case Studies in Realizing Green Buildings*; Sayigh, A., Ed.; Elsevier Science & Technology: San Diego, 2013; pp 227−255. DOI: 10.1016/B978-0-12-397269-9.00009-8.

(16) Stiles, W. S.; Burch, J. M. N.P.L. Colour-matching Investigation: Final Report (1958). *Optica Acta: International Journal of Optics* **1959**, *6* (1), 1−26.

(17) ASTM International. Standard Practice for Computing the Colors of Objects by Using the CIE System. In *E308*; ASTM International, 2018; Vol. *E308*, p 45. DOI: 10.1520/e0308-18.

(18) Light Sources and Illuminants for Colorimetry. In *Standard Colorimetry*; Oleari, C., Ed.; Wiley, 2015; pp 189−208. DOI: 10.1002/9781118894477.ch8.

(19) Goodman, T. M., International standards for colour. In *Colour Design*; Elsevier, 2012; pp 417−452. DOI: 10.1016/b978-0-08-101270-3.00018-7.

(20) Javoršek, D.; Javoršek, A. Colour management in digital textile printing. *Coloration Technology* **2011**, *127* (4), 235−239.

(21) Ikeuchi, K. *Computer Vision.* **2014**, DOI: 10.1007/978-0-387-31439-6.

(22) Setchell, J. S., Colour description and communication. In *Colour Design*; Elsevier, 2012; pp 99−129. DOI: 10.1016/b978-0-08-101270-3.00004-7.

(23) Shendye, A. V. *Study of Metamerism and Inconstancy of Basic Color System Used in Wood Grain Laminates*; Western Michigan University: Kalamazoo, MI, 2011; p 71.

(24) Sharma, A., *Understanding color management*; Wiley: Hoboken, NJ, 2018. DOI: 10.1002/9781119223702.

(25) Prasad, D. K.; Nguyen, R.; Brown, M. S., Quick Approximation of Camera's Spectral Response from Casual Lighting. In *2013 IEEE International Conference on Computer Vision Workshops*; IEEE, 2013; pp 844−851. DOI: 10.1109/iccvw.2013.116.

(26) Marszalec, E.; Pietikainen, M. In Online color camera calibration, *Proceedings of 12th International Conference on Pattern Recognition*, 9−13 Oct 1994; 1994; Vol.*1*, pp 232−237. DOI: 10.1109/ICPR.1994.576263.

(27) Gilmor, C.; Balke, S. T.; Calidonio, F.; Rom-roginski, A., In-Line Color Monitoring of Polymers During Extrusion Using a Charge Coupled Device Spectrometer: Color Changeovers and Residence Time Distributions. *Polymer engineering and science*; Wiley, 2003; Vol. *43* (2).

(28) Wen, B.-J., Standard Measurement Geometries. In *Encyclopedia of Color Science and Technology*; Luo, M. R., Ed. Springer New York: New York, NY, 2016; pp 1170−1174. DOI: 10.1007/978-1-4419-8071-7_361.

(29) Carr, K. F. Integrating sphere theory and applications Part I: Integrating sphere theory and design. *Surface Coatings International* **1997**, *80* (8), 380−385.

(30) Carr, K. F. Integrating sphere theory and applications Part II: Integrating sphere applications. *Surface Coatings International* **1997**, *80* (10), 485−490.

(31) ASTM International. Standard Test Method for Multiangle Color Measurement of Metal Flake Pigmented Materials. In *E2194-14*; ASTM International, 2017; Vol. *E2194−14*. DOI: 10.1520/e2194-14r17.

(32) ASTM International. Standard Test Method for Multiangle Color Measurement of Interference Pigments. In *E2539-14*; ASTM International, 2017; Vol. *E2539−14*. DOI: 10.1520/e2539-14r17.

(33) Sun, J.; Bhushan, B.; Tong, J. Structural coloration in nature. *RSC Advances* **2013**, *3* (35), 14862.

(34) Painter, T. H.; Paden, B.; Dozier, J. Automated spectro-goniometer: A spherical robot for the field measurement of the directional reflectance of snow. *Rev. Sci. Instrum.* **2003**, *74* (12), 5179−5188.

(35) Learn more about the science of Spectroscopy. http://www.microspectra.com/component/content/article/35-technical-support/59-spectroscopy-science (accessed Aug 31, 2021).

(36) Landry, A.; Son, T. V.; Martucci, A.; Haché, A. Color switching by polarization effects in phase change materials. *Opt. Commun.* **2020**, *459*, No. 124957.
(37) Sharma, V.; Park, K.; Srinivasarao, M. Colloidal dispersion of gold nanorods: Historical background, optical properties, seed-mediated synthesis, shape separation and self-assembly. *Materials Science and Engineering: R: Reports* **2009**, *65* (1−3), 1−38.
(38) Eremin, Y. A., Scattering Theory. In *Encyclopedia of Modern Optics*; Guenther, R. D., Ed.; Elsevier, 2005; pp 326-330.
(39) Montazer, M.; Harifi, T., Nanofinishing: Fundamental principles. In *Nanofinishing of Textile Materials*; Elsevier, 2018; pp 19−-34. DOI: 10.1016/b978-0-08-101214-7.00002-9.
(40) Kannari, F., Raman Scattering. In *Encyclopedia of Modern Optics*; Guenther, R. D., Ed.; Elsevier, 2005; pp 309−314.
(41) Komatsu, I.; Aoki, H.; Ebisawa, M.; Kuroda, A.; Kuroda, K.; Maeda, S. Color change mechanism of niobium oxide thin film with incidental light angle and applied voltage. *Thin Solid Films* **2016**, *603*, 180−186.
(42) Bragg, W. H.; Bragg, W. L. The reflection of X-rays by crystals. *Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character* **1913**, *88* (605), 428−438.
(43) Yu, L. Color Changes Caused by Conformational Polymorphism: Optical-Crystallography, Single-Crystal Spectroscopy, and Computational Chemistry. *The Journal of Physical Chemistry A* **2002**, *106* (3), 544−550.
(44) Filhol, J.-S.; Deschamps, J.; Dutremez, S. G.; Boury, B.; Barisien, T.; Legrand, L.; Schott, M. Polymorphs and Colors of Polydiacetylenes: A First Principles Study. *J. Am. Chem. Soc.* **2009**, *131* (20), 6976−6988.
(45) Teyssier, J.; Saenko, S. V.; Van Der Marel, D.; Milinkovitch, M. C. Photonic crystals cause active colour change in chameleons. *Nature Communications* **2015**, *6* (1), 6368.
(46) Color measurement. https://www.shimadzu.com/an/service-support/technical-support/technical-information/uv-ap/color.html (accessed Feb 15, 2021).
(47) Swinehart, D. F. The Beer-Lambert Law. *J. Chem. Educ.* **1962**, *39* (7), 333.
(48) Underwood, S.; Mulvaney, P. Effect of the Solution Refractive Index on the Color of Gold Colloids. *Langmuir* **1994**, *10* (10), 3427−3430.
(49) Lee, S.; Shin, H.-J.; Yoon, S.-M.; Yi, D. K.; Choi, J.-Y.; Paik, U. Refractive index engineering of transparent ZrO_2−polydimethylsiloxane nanocomposites. *Journal of Materials Chemistry* **2008**, *18* (15), 1751−1755.
(50) Wiederseiner, S.; Andreini, N.; Epely-Chauvin, G.; Ancey, C. Refractive-index and density matching in concentrated particle suspensions: a review. *Experiments in Fluids* **2011**, *50* (5), 1183−1206.
(51) Sacher, R. Microscope Immersion Oil. *Microscopy Today* **2000**, *8* (8), 33−35.
(52) Groever, B.; Heshmat, B.; Raskar, R. Tyndall Windows: Tunable Scattering of Disordered Solid−Liquid Matching Mixtures. *ACS Photonics* **2016**, *3* (6), 930−935.
(53) Niskanen, I.; Suopajärvi, T.; Liimatainen, H.; Fabritius, T.; Heikkilä, R.; Thungström, G. Determining the complex refractive index of cellulose nanocrystals by combination of Beer-Lambert and immersion matching methods. *Journal of Quantitative Spectroscopy and Radiative Transfer* **2019**, *235*, 1−6.
(54) Brewster, D. IX. On the laws which regulate the polarisation of light by reflexion from transparent bodies. By David Brewster, LL. D. F. R. S. Edin. and F. S. A. Edin. In a letter addressed to Right Hon. Sir Joseph Banks, Bart. K. B. P. R. S. *Philosophical Transactions of the Royal Society of London* **1815**, *105* (0), 125−159.
(55) Beckers, M.; Weise, B.; Kalapis, S.; Gries, T.; Seide, G.; Bunge, C. A. Basics of light guidance. *Polymer Optical Fibres* **2017**, 9−46, DOI: 10.1016/b978-0-08-100039-7.00002-6.
(56) Redner, A. S.; Hoffman, B. R. *How to Measure Stress in Transparent Plastics* 2017. https://www.strainoptics.com/wp-content/uploads/2017/11/How-to-Measure-Stress-in-Transparent-Plastics.pdf (accessed May 08, 2020).
(57) Mueller, H. The Theory of Photoelasticity. *J. Am. Ceram. Soc.* **1938**, *21* (1), 27−33.
(58) Botos, J.; Murail, N.; Heidemeyer, P.; Kretschmer, K.; Ulmer, B.; Zentgraf, T.; Bastian, M.; Hochrein, T. In Color measurement of plastics - From compounding via pelletizing, up to injection molding and extrusion, *Proceeding of PPS-29: AIP Conference Proceedings*; Nuremberg, Germany, Altstädt, V.; Keller, J.-H.; Fathi, A., Eds.; AIP: Nuremberg, Germany, 2013; pp 16−19. DOI: 10.1063/1.4873725.
(59) *Measurement of PET Flake or Pellet Discoloration*; The Association of Plastic Recyclers, 2018, p 3. https://plasticsrecycling.org/images/Design-Guidance-Tests/APR-PET-S-02-discoloration-screening.pdf.
(60) ASTM International. Standard Test Method for Color Determination of Plastic Pellets. In *D6290*; ASTM International: West Conshohocken, PA, 2019; Vol. *D6290*, p 7. DOI: 10.1520/d6290-19.
(61) ASTM International. Standard Test Method for Polyurethane Raw Materials: Instrumental Measurement of Tristimulus CIELAB Color and Yellowness Index of Liquids. In *D7133*; ASTM International: West Conshohocken, PA, 2016; Vol. *D7133*, p 5. DOI: 10.1520/d7133-16.
(62) ASTM International. Standard Test Method for Color and Color-Difference Measurement by Tristimulus Colorimetry. In *E1347*; ASTM International: West Conshohocken, PA, 2015; Vol. *E1347*, p 5. .
(63) ASTM International. Standard Practice for Calculation of Color Tolerances and Color Differences from Instrumentally Measured Color Coordinates. In *D2244*; ASTM International: West Conshohocken, PA, 2016; Vol. *D2244*, p 12. .
(64) ASTM International. Standard Test Method for Color of Liquids Using Tristimulus Colorimetry. In *D5386*; ASTM International: West Conshohocken, PA, 2016; Vol. *D5386*, p 4. DOI: 10.1520/d5386-16.
(65) ASTM International. Standard Test Method for Color of Transparent Liquids (Gardner Color Scale). In *D1544*; ASTM International: West Conshohocken, PA, 2018; Vol. *D1544*, p 3. .