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Post-consumer polymers (PCR) for color retention of delicatessen meats and elucidation of the light blocking mechanism

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ABSTRACT

Increased light blocking properties of extruded films can be realized by sustainable, post-consumer recycled (PCR) polymers. This study elucidates the light blocking mechanism of these films within the ultraviolet-visible region (UV–Vis) via a novel optical measurement and electron microscopy analysis. A spectrometer and integrating sphere were mounted on a translational stage opposite a light source to measure the apparent absorbance as a function of distance. It was determined that a mixed scattering/reflection mechanism is present for virgin/PCR high density polyethylene (HDPE) blends with increased scattering in the ultraviolet and both scattering and reflection in the blue-visible. An electron microscopy study further suggests that the unique optical properties may be due to the well-dispersed nano-domains of aluminum, oxygen, and silica with increasing PCR content in addition to changes in crystalline domains reported previously. This inspired the application of the material as a light fixture filter for preserving light sensitive products. The preservation efficiency of light sensitive specimens under light emitting diode (LED) illumination was evaluated quantitatively (CIE L*a*b* color space) and qualitatively (digital imaging) as a function of time. Using roast beef as a model system, the maximum red color change (a*) of non-filtered roast beef specimens was realized approximately 55% faster than the filtered ($\Delta a^* = 7.1$) in simulated retail display conditions. The improved color retention under filtered light can be attributed to increased light scattering across the blue wavelength range (440–485 nm) reducing light exposure near the maximum absorption band of myoglobin. Reduction of blue light exposure inhibits metmyoglobin production and meat discoloration. Data presented in this study suggest that PCR polymers can tune light blocking properties, providing a means to increase the color retention of light sensitive foods while simultaneously diverting food and plastic waste from landfills.

1. Introduction

Global plastic production surpassed 348 million tons in 2017 with the majority of these plastics intended for single use applications [1]. Landfill diversion strategies are needed to redirect plastic waste as consumer demand increases municipal solid waste accumulation. High-density polyethylene (HDPE) is widely used in consumer and industrial applications due to its high strength and stability, contributing 17.6% of plastic waste—the third largest plastic category in municipal solid waste [2]. HDPE is a highly problematic material in landfills as its stability and low susceptibility to environmental factors limits its degradation. However, these attributes are useful in retaining physical properties in secondary recycling practices. Introducing post-consumer recycled (PCR) material into virgin resin is therefore a highly promising route to reduce waste. A previous study [3] demonstrated that the PCR content alters key properties of high density polyethylene films. Pure HDPE films of similar thickness to those used in this work (3–5 mil) are commonly found in a number of forms including plastic sheeting for floor/furniture protection, frosty die cut bags, and cereal/cake mix bags. Increasing the PCR concentration resulted in molecular changes in the polymer blend via increased terminal substitutions (vinyl and carbonyl) and changes of the crystalline melting behavior. The molecular and crystalline changes induce drastic variation in functionality, specifically in the film's absorptivity in the ultraviolet region [4–7]. However, the detailed mechanism behind the increased absorptivity has yet to be determined.

In this study, we designed a new instrument to study the optical properties of PCR films, with examination of microstructure and composition through high resolution transmission electron microscopy (HR-TEM). Furthermore, we presented the effectiveness of blending PCR with virgin HDPE for preventing meat discoloration in commercial retail

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display case environments. A custom light scattering instrument was built to identify differences in absorption/reflection and scattering properties in the ultraviolet-visible spectrum. A xenon white light illuminates through the sample with a fixed aperture, and the apparent absorbance spectrum is measured as a function of distance from the sample (Fig. 1). With the detector at zero distance, all light entering the integrating sphere is influenced by reflection, absorption, and scattering. As the detector is moved away from the sample, light scattering events reduces the amount of light entering the detector and the apparent absorbance increases. Therefore, increasing apparent absorbance as a function of distance from the sample is indicative of scattering events and conversely, no change in the apparent absorbance is indicative of purely absorbance/reflective properties. The material structures responsible for optical property changes were determined via transmission electron microscopy and energy-dispersive X-ray spectroscopy (EDS). Through this technique, the details of the nano-domains in material composition (with varying PCR content) were identified.

By determining the film's optical properties, appropriate end-use applications can be appointed. Wavelength dependent scattering and absorption properties are potentially useful for improvement of color retention of light sensitive foods. Existing light emitting diode lighting in commercial retail display cases can significantly and rapidly degrade food products and packaging ink, reducing shelf life and consumer acceptability. The color of food products, such as meats, cheeses, and packaging materials has been shown to fade from light induced degradation reactions [8–11]. To retain viable consumer appearance for delicatessen ready to eat products such as roast beef and ham, slicing for full-service sale are commonly performed multiple times per day. There is significant additional labor costs associated with this approach, which reduces, but does not eliminate, food waste. The United States Department of Agriculture estimated that 30–40% of food (up to 133 billion pounds and 161 billion USD) in the United States is wasted annually at retail and consumer levels [12]. Globally, it has been estimated that as much as half of all food grown is lost or wasted prior to reaching the consumer, partially due to real and *perceived* loss of quality from visual changes during retail display [13]. Therefore, technology and retail display methods to improve consumer perception (and shelf life) are critical in reducing economic loss and food waste.

Delicatessen meats such as rare roast beef serve as an excellent model system to investigate the influence of light exposure on consumer perception due to rapid noticeable and quantifiable degradation [14,15]. This process occurs due to the oxidative degradation transformation of myoglobin to metmyoglobin [16–18]. The oxidation transformation initiates a change in redness (quantitatively described as a* in the L* a* b* color space). Metmyoglobin production from myoglobin is catalyzed when the product is exposed to light with myoglobin's absorptivity across blue wavelengths (440–485 nm) being the most sensitive to light degradation. Discolored meat causes significant changes in customer purchasing patterns, and it was determined that sales decrease by two times when 20% metmyoglobin pigment is present [19]. We hypothesized that limiting exposure to blue light will reduce the transformation of myoglobin to metmyoglobin, enabling increased shelf-life delicatessen meats. Due to the low optical clarity of PCR HDPE films, we sought to retrofit the light filtering film directly to the surface of the LED bulb. In all cases, only the LED bulb is retrofitted with the PCR filtering material.

To mimic retail conditions, a commercial open, multi-deck, self-service display case was equipped with commercially available LED canopy and shelf fixtures. The PCR HDPE film was adhered to the surface of the lighting fixtures to provide filtered lighting conditions when applicable. Ten samples of each product were used in each trial, with five in direct light (filtered or unfiltered) and five placed under aluminum foil to serve as the negative control (absence of light). Digital images and quantitative colorimetric data (L*a*b* values) were collected as a function of time for eight days. To ensure proper and repeatable light intensity exposure of the samples, two trials were completed: 1) as received LED lights alone, and 2) the same LED lights with the light blocking material attached. In both trials, test specimens were placed on the same shelves and locations to ensure the most accurate comparison of colorimetric changes due to the presence of the light filters. It was demonstrated that with the application of the filters, the maximum color change in a* (7.1) was 55% slower, compared to the unfiltered counterpart. Under retail conditions, it can be reasonably assumed that there are no adverse microbial loads, and the products are prepared under Good Manufacturing Processes. Therefore, we only assessed colorimetric changes of the roast beef as an indicator of consumer acceptability and product quality. Together, the results of this study impact the reduction of landfill accumulation of food and plastic waste, potentially providing economic growth due to decreased labor costs.

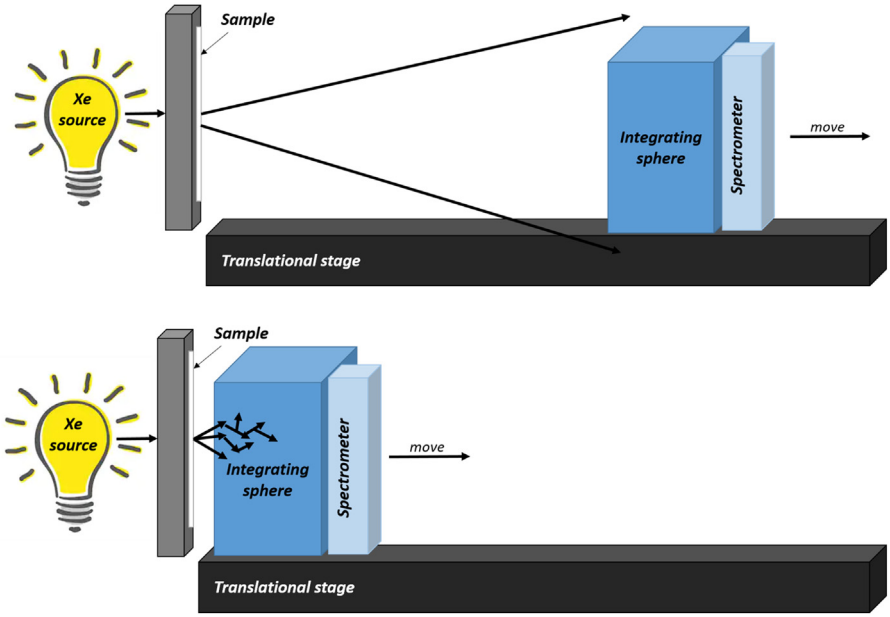

Fig. 1. Light scattering instrument composed of a spectrophotometer and translation stage to differentiate optical behaviors as a function of distance.

2. Materials and method

2.1. Sample preparation

Post-consumer high-density polyethylene and virgin high-density polyethylene were hand blended for homogeneity to achieve PCR:virgin ratios of 0, 20, 40, 60, 80, and 100% by weight. Prior to extruding, each blend was dried at 100 °C to remove adsorbed atmospheric water. The dried blends were then extruded with a single screw extruder (Killion) with three barrel heat zones (set to 190.5 °C), a coupler heat zone (set to 204.2 °C), and thermally controlled two zone coat hanger style die (set to 204.4° C). The molten extrudate was collected on a J stack take up roller set at a fixed distance from the die. Sample thickness was verified as 3–5 mil.

2.2. Light scattering measurements

A UV–Vis spectrometer (Ocean Optics QEPRO) was used in tandem with an integrating sphere (Ocean Optics FOIS-1) to measure the irradiance from a pulsed xenon light source (Hamamatsu L9455–22). The spectrometer was pre-configured for 1 nm resolution with a spectral range of 200–1000 nm. The absorbance of light passing through the filter was measured as a function of distance (10–110 mm), with the spectrophotometer moving away from the detector on a motorized stage (Thorlabs LTS 300, Fig. 1). Raw light was projected through the sample holder aperture and onto the integrating sphere input aperture. To account for beam divergence, reference levels were taken at each interval. Fiber bend radius was maintained via combined translation of the spectrometer and stage (reference readings are reproducible within a 0.3% threshold). Three scans were averaged at each point to improve signal and to average pulse-to-pulse variation from the light source.

2.3. Transmission electron microscopy (TEM) characterization

Bright-field transmission electron microscopy images were acquired on a 200 kV JEOL 2100 scanning/transmission electron microscope. Tecnai F20 microscope operating at 200 kV was used to acquire high angle annular dark field scanning transmission electron microscopy (HAADF-STEM) images and energy dispersive X-ray spectroscopy spectra. The films were immersed in sucrose solution-embedded block, frozen at −120 °C, and then sectioned by using a Leica UC6 ultramicrotome with a FCS6 cryo unit (Leica-microsystems.com) and a diamond knife. Thin sections of the film (90 nm) were then transferred onto carbon-coated copper grids at room temperature for TEM characterization. Subsequently, the grids were stained with 2% Rutheniumtetroxide vapor for a period of about 15 min to aid in contrast differentiation [20].

2.4. Display case configuration and sample placement

An open, multi-deck, self-service display case (Hill Phoenix, O5DM-8; Fig. S1a.) was equipped with LED canopy fixtures (Clearvoyant v4 HO P105992C) and shelves (Clearvoyant v4 SO P105967F) coupled to a 100 W 24VDC output LED driver (P096368H). The first trial consisted of the display case utilizing the as received ("standard") light fixtures. In the second trial, each light fixture was retrofitted with the custom blend light blocking material, adhered to the lens cover with adhesive strips (Fig. S1a. and S2.). The filter was comprised of 80% waste diverted post-consumer recycled high-density polyethylene and was produced as described previously [5].

Rare roast beef was sliced and procured from a local retail outlet within 30 min prior to each trial to obtain the freshest and most consistent product for each trial. This involved transportation of the product in coolers kept at 4 °C prior to placement in the retail display case. To begin the study, each sliced specimen was enclosed in a commercially available polyethylene package then placed on the second shelf of the display case (Fig. S1b.). Dark control roast beef samples (absence of light) were placed on the third shelf and covered with aluminum foil (without creating a hermetic seal) to quantify color changes in the absence of light. Comparison of the color changes of the dark control samples to those in direct light enables a direct investigation of the impact of light intensities on color changes of each specimen.

2.5. Quantitative colorimetric measurements

Color changes of the rare roast beef specimens were quantified as a function of exposure time using a BYK spectro-guide 45/0. A xenon light source with an incident light color of a D65 illuminant was utilized to calculate color changes with a 10° observer angle according to Tapp et al. [21]. Illuminant and observer were selected in the instrument software settings. Color changes were quantified using the CIE L*a*b* color space coordinates. The color space coordinates are expressed as three numerical values: the L* coordinate represents lightness following in $0 \le L^* \le 100$ (L = 0 for black, L = 100 for white), the a* coordinate represents the red-green axis, (positive values for red and negative for green), and the b* coordinate represents the blue-yellow color axis, (positive values for yellow and negative for blue) [22]. Measurements for each specimen were recorded in the same X-Y spatial coordinates to avoid and reduce the variability in sample homogeneity that may influence quantitative colorimetric analysis as shown in Fig. S3.

Differences in color are quantitatively described by calculating the magnitude of the color change across the three-dimensional color space and expressed as the term ΔE (Eq. 1) [23].

$$\Delta E = \sqrt{\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}} \quad (1)$$

ΔL^*: is the difference in brightness.

Δa^* and Δb^*: are the differences in the color coordinates a* and b*, respectively.

Direct comparisons of color changes (ΔE) of each specimen were classified according to the categories established previously [24].

- 0–1 A normally invisible difference,
- 1–2 Very small difference,
- 2–3.5 Medium difference,
- 3.5–5 An obvious difference,
- > 6 A very obvious difference.

2.6. Incident radiation measurements

An STS micro spectrometer (Ocean Optics) was utilized to measure the incident radiation (absolute irradiance) from the LED lights with and without the filter. The spectrometer was configured to measure absolute irradiance of the visible spectrum (average of three scans with ten second exposure times per measurement). Spectral measurements were collected in the same X-Y spatial coordinates on the shelf where samples were placed (red numbers Fig. S1b.).

2.7. Digital image recording

Digital images of each specimen were recorded as a function of time using a full frame (35 mm equivalent) Nikon D750 digital camera equipped with a Nikon 24-120 mm lens (AF-S Nikkor 24-120 mm f/4G ED VR). Digital images were collected of each specimen inside a BYK spectra light box equipped with a D65 illuminant to provide optical representations of the quantitative data collected from the BYK colorimeter.

3. Results and discussion

3.1. Light filter mechanism

To tune light blocking properties for specific light sensitive materials using PCR polymers, it is necessary to elucidate the light filtering mechanism. This enables increased protection of light sensitive products with differing sensitivities across the ultraviolet-visible spectrum. A custom light scattering instrument was fabricated (Fig. 1.) utilizing a spectrophotometer on a translation stage to measure the absolute intensity of light in the ultraviolet and visible spectrum as a function of distance from the light blocking material. To validate trends in light scattering events for materials, fused quartz specimens were acquired with either a ground surface (diffusion/scatterer) or a metal deposition coating (absorber/reflector). With these standards, three possible optical phenomena can be discerned: scattering, absorption, and reflection.

The apparent absorbance was measured for PCR HDPE films (0–100% PCR) as a function of distance from the light blocking material (10–110 mm). With the introduction of distance, scattering events throughout the ultraviolet-visible spectrum can be probed. The apparent absorbance for each experiment was reported as an absorption ratio (Eq. 2) to facilitate understanding of reflection, scattering, and absorption events. A purely absorbing/reflecting material would be expected to exhibit no change in absorbance with increasing distance, yielding a ratio value of 1. Conversely, a scattering mechanism would possess an absorbance ratio greater than 1.

$$AbsorbanceRatio = Absorbance_{distance} : Absorbance_{initial} \quad (2)$$

To verify the methodology, two optical lenses were used: one known reflector (UV Fused Silica Reflective Filter, OD: 0.1, Thor Labs) and one known diffuser (UV Fused Silica Ground Glass Diffuser, Grit: 1500, Thor Labs). Prior to beginning the study, the optical values of lenses were verified as in agreement with the reported values from the supplier. The diffusing and absorbing lenses were then measured with the new technique. The absorbance ratio did not change throughout the UV–Vis region as a function of distance for the purely reflecting lens (Fig. S4.). In contrast, the diffusing lens demonstrated a linear increase in the absorbance ratio as a function of distance (Fig. S5.).

After the instrument and method was verified with the absorbing and scattering/reflecting lens, HDPE films of varying PCR content were measured (Fig. 2. and S6.). It was determined that the introduction of PCR content increases the scattering efficiency throughout the spectrum (greatest increase occurs 260–500 nm). Virgin HDPE blown films possess low levels of scattering in the ultraviolet portion of the spectrum (Fig. 2.). The mechanism for the drastic increase in light scattering may be due to the introduction of new phases in the PCR films. Larena and Pinto [25] demonstrated that scattering in regenerated cellulose tubular films was a result of the mismatch of refractive indices from increased amorphous fraction due to repeated recycling. The redistribution of crystalline domain sizes may also influence the degree of scattering [26]. In the same regard, the relative degree of scattering increases linearly with PCR content. For all light filtering films measured (0–100% PCR HDPE), the absorption ratio suggests a relatively higher degree of scattering from 260 nm into the lower end of the visible spectrum (400–500 nm) (Fig. 2.). Absorbance ratios were determined to increase up to 500 nm, suggesting that higher PCR concentrations improve the film's scattering properties for visible/ultraviolet blocking properties. In the lower UVC region, it is shown that absorbance dominates the light blocking mechanism. It is hypothesized that this occurs due to the production of carbonyls (absorption band at 180–220 nm) in the recycling process [27]. The combination of scattering and absorption may be responsible for the optical properties observed in the extruded PCR HDPE films.

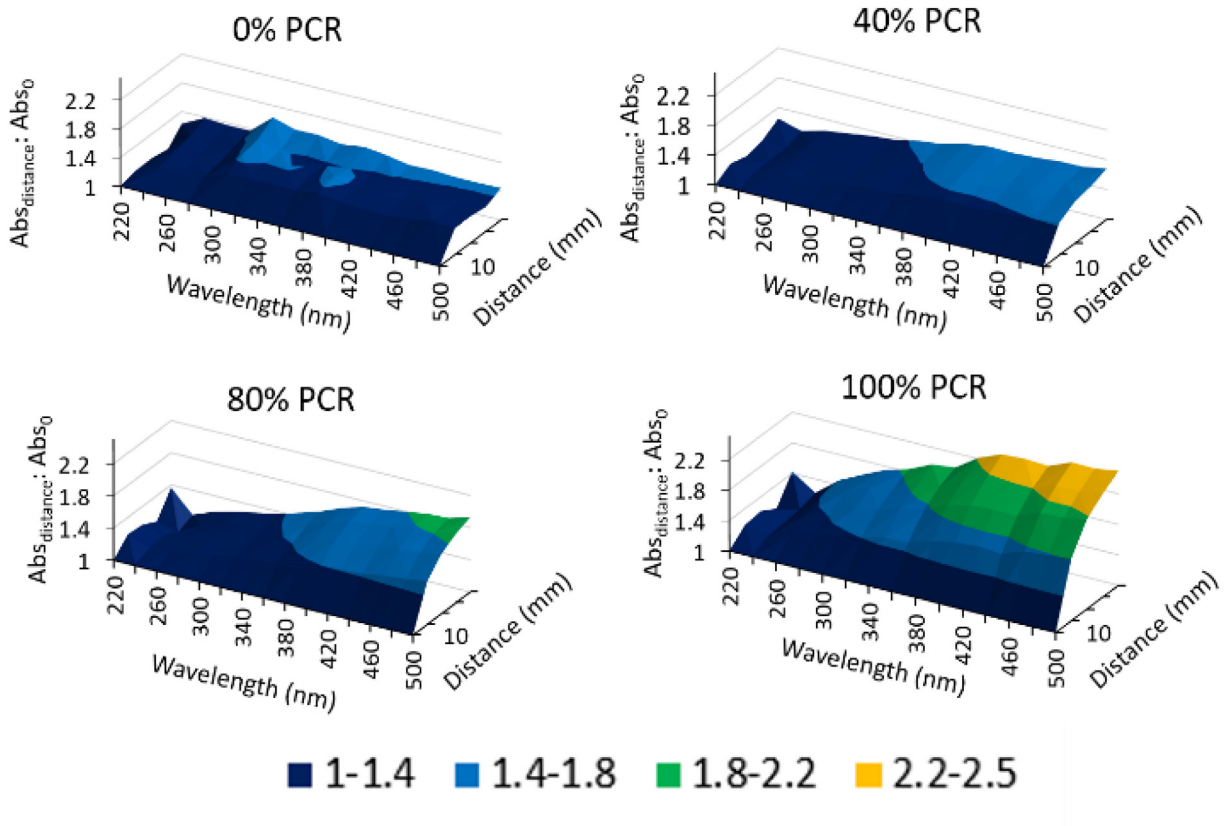

Fig. 2. Contour plot of the light filters as a function of detector distance and wavelength.

In addition to understanding the apparent absorption/ scattering properties of the PCR/virgin HDPE films, reflection spectra were collected via colorimeter to quantify light reflection as function of PCR concentration. In this way, it is possible to differentiate absorbance and reflectance properties aside from the separate phenomena of scattering. The experiments determined that increasing PCR content increases light reflection, particularly at wavelengths greater than 560 nm (Fig. 3.). However, at 560 nm it appears that no light is reflected and is either absorbed or transmitted. We hypothesize that absorption occurs due to the conjugation of terminal vinyl groups [26]. Overall, it was demonstrated that PCR content introduces new optical properties to the film, increasing the scattering and reflection properties of the material. This is hypothesized to be a result of new nano-sized domains of inorganic materials identified via TEM analysis [26,28].

To further understand the mechanism of absorption/scattering properties, microstructures of films with different PCR content were characterized by transmission electron microscopy. As seen in Fig. S7., increasing PCR content induces nanoscale changes in material composition. Compared to the virgin HDPE film, films including PCR content appear to have a large amount of well-distributed domains of 50–200 nm size. The compositions of the nano-sized domains were analysed via EDS (Fig. S8.). EDS reveals the domains are enriched with Si, Al, and O, suggesting the presence of Al_2O_3 and SiO_2. Since the PCR plastic is landfill diverted and the sourcing is not controlled, Si and Al could be additives or fillers (talc, etc.) or formed in situ [29]. Specifically, shear stress realized on macro-sized particles may be responsible for the formation of dispersed nano-sized domains in extrusion processing. These well-dispersed domains introduce tremendous amounts of interface in the system and may induce significant degrees of scattering. The scattering spectrum may be correlated with the domain size and distribution. Indeed, nanoparticles have been widely applied in coating materials as opacifiers to modulate the scattering of different wavelengths of light [30,31]. As a result, the TEM results serve as indirect evidence to support the hypothesis that the formation of nano-sized domains causes scattering due to the formation of new interfaces.

3.2. Light blocking spectrum of recycled polyethylene film

Critically important to display case design is the product appearance under standard display conditions. As a result, technologies designed to reduce light induced degradation must not alter product color observed by consumers as this may impact consumer perception of the products. Differences between absolute irradiance spectra of the LED lights with and without the filter material were measured in the display case. Measurements indicate a light intensity reduction

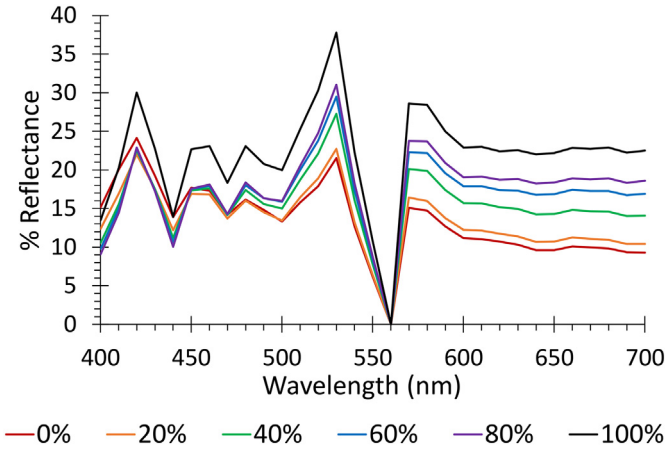

Fig. 3. Reflectance spectra of HDPE films as function of PCR concentration.

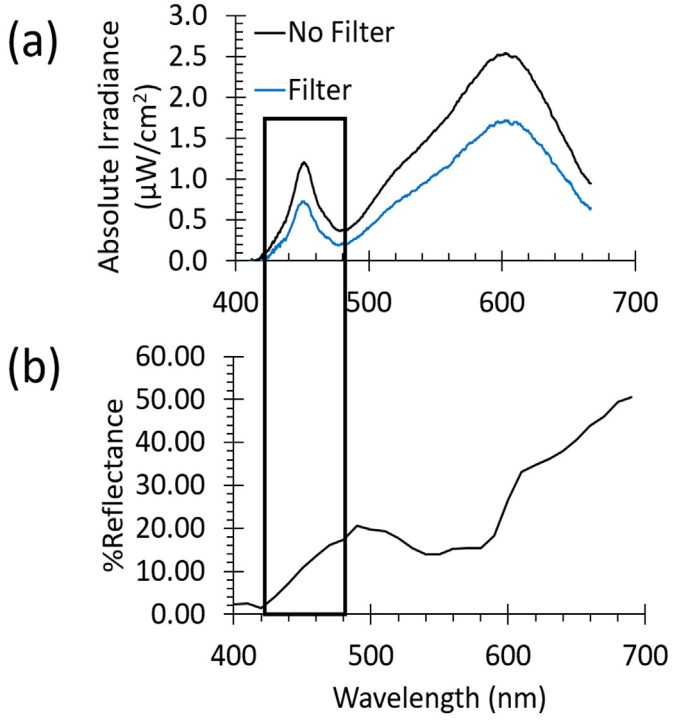

Fig. 4. (a) Measured irradiance spectra from retail display case LED with and without filter and (b) reflectance of the roast beef with no filter.

for the display case LED light (Fig. 4a.), but the reduction appears to be uniform throughout the spectrum which is anticipated to influence consumer perception of colors equally. It is important to note that the LED lights emit a noticeably strong band between 420 and 480 nm compared to other wavelengths (Fig. 4a.). This band is adjacent to the maximum absorption wavelength of myoglobin at 405 nm which could be a significant component in rapid color degradation. The roast beef specimens were measured to reflect the lowest amount of light in this region (Fig. 4b.) [32]. Reduced reflectance can generally be correlated to increased light absorption as significant light transmission is not expected, and with the measured reflectance of roast beef being less than 20% between 445 and 480 nm, we can infer that blue wavelength exposure influences meat discoloration. The similarities between the LED emission, efficient light scattering of the light blocking material, and roast beef absorption supports utilizing the filter for color retention improvement.

3.3. Quantitative colorimetric analysis of roast beef

Color differences of filtered roast beef samples (Fig. 5.) were compared to those exposed to standard LED retail display conditions (without filter). It is well known that protein such as rare roast beef and fresh beef will undergo color changes due to the increase of metmyoglobin. As a result, we hypothesize that adequately filtering and/or decreasing the direct exposure of light on fresh meat products will decrease redness color change (a^*) associated with myoglobin oxidation.

The filter was determined to reduce the overall color change (ΔE) of rare roast beef samples (Fig. S9.) compared to unfiltered samples. Colorimetric analysis indicated the presence of at least a medium color difference after only approximately an hour and a half of light exposure ($2 < \Delta E < 3.5$) for unfiltered samples (Fig. S9.). In contrast, a ΔE value of ~1 in the same timeframe for filtered roast beef samples was realized which is normally not distinguishable from the initial roast beef color (Fig. S9.). There was a minimum of a medium distinguishable difference between the samples exposed under the filter and those without filter

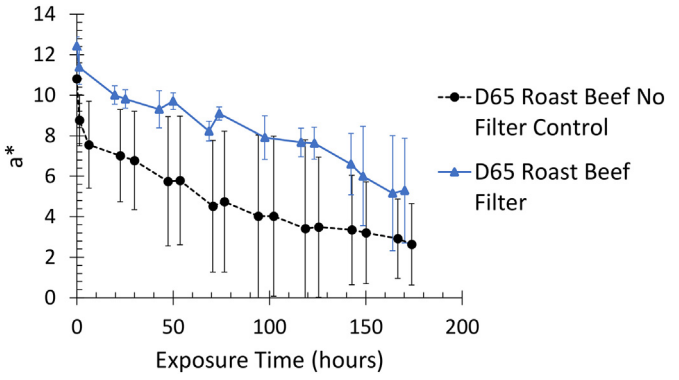

Fig. 5. Calculated magnitude of red/green color change (a*) for roast beef samples as a function of time with and without the filter using a D65 illuminant.

up to 50 h of exposure (difference of ΔE values between 2 and 3). The difference in color changes becomes more distinguishable as the exposure time continues (Fig. S9.).

To further understand the influence of the filter on color changes of rare roast beef specimens, ΔE values of the exposed samples were compared to those from specimens conditioned without light exposure (dark control). This comparison isolates the influence of light exposure on color changes as dark control specimens were shielded from light except when collecting digital images and colorimetric data in the same fashion as those exposed to light. The quantitative colorimetric data indicated that there was no distinguishable difference in color between the roast beef specimens exposed to filtered light and dark control specimens up to 120 h of exposure (Fig. S10.), i.e., difference in ΔE was below one [24]. Furthermore, the difference between filtered/ exposed roast beef specimens and dark control specimens reached a maximum difference of $\Delta E = 3.7$ throughout the entire trial. The equivalent difference in color change for the samples (i.e., change in ΔE of 3.7) without the filter was measured to occur at 53 h of exposure which is over 100 h less than the samples exposure under the filtered light.

To interpret the key factors which contribute to the total color change (ΔE) of roast beef samples, the significance of each color variable (L*, a*, b*) was determined. It was shown that L* increased gradually over time with little influence from the light filter as there was no significant difference between sample brightness and corresponding controls (Fig. S11.). On the other hand, a* remained consistently higher for filtered samples compared to non-filtered samples, demonstrating increased red color retention (Fig. 5.). It became clear that the a* variable makes significant contributions to ΔE, providing a quantitative explanation for the improved roast beef appearance as a function of time. Similar to L*, no significant change in b* was observed between the samples and controls with application of the light filter (Fig. S11.). Therefore, improvements in total color change with application of the light filtering technology occurred due to reduced change in a*, a measure which quantifies the vital element of redness in rare meats [33]. It is also determined that the filter offers greater consistency amongst samples, and the unfiltered samples are more variable in the values for color change (Fig. 5.).

3.4. Qualitative colorimetric changes in roast beef color

Qualitative investigations of color changes for roast beef specimens confirm the quantitative data calculated with the D65 illuminant parameter (Fig. S9., S10., and S11.). However, the roast beef exposed in the display case with the filter retained a redder color for a longer period, compared to the non-filtered specimens (Fig. 6.).

4. Conclusion

Heightened concern over the impact of waste plastics in both marine and terrestrial environment necessitates a means to reduce, reuse, and add value to post- consumer plastics. Previous studies in our lab have shown that post-consumer recycled (PCR) content affects the molecular and physical properties of HDPE extruded films. This study sought to elucidate the mechanism associated with differing light blocking capabilities of polymers that contain post-consumer recycled materials. A new technique involving a spectrometer and integrating sphere on a translational stage was developed to discern scattering events within the ultraviolet-visible spectrum. It was demonstrated that increasing PCR content increases the apparent absorption and reflection properties

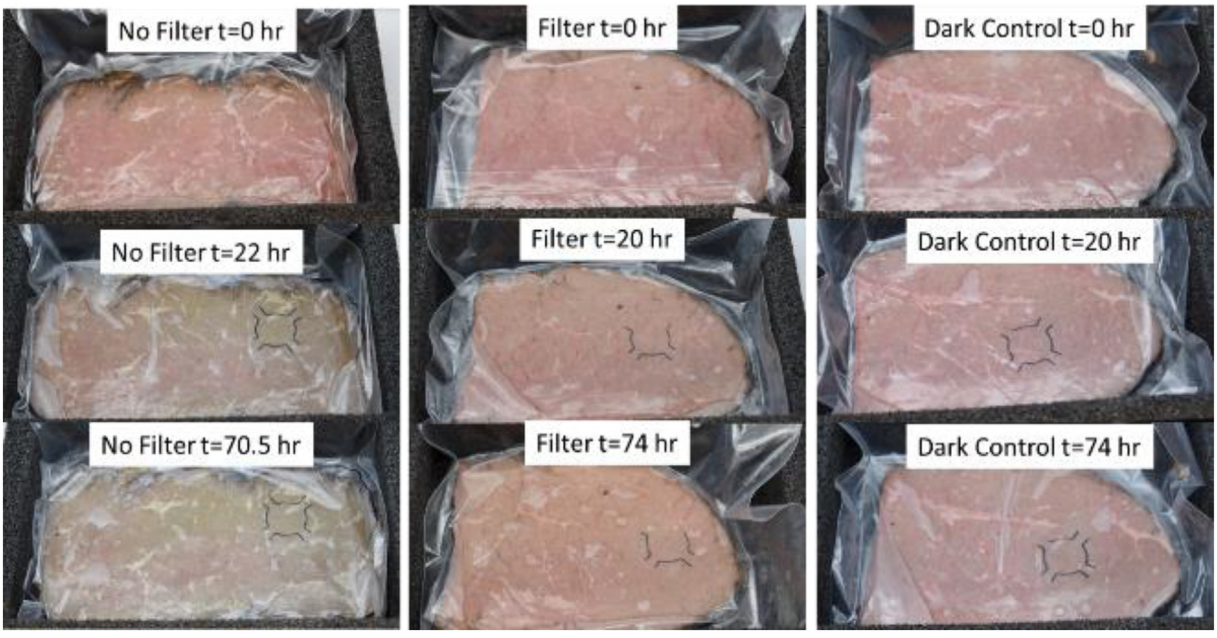

Fig. 6. Representative rare roast beef specimens in commercially available polyethylene packages conditioned in an LED equipped display case without the fixture filter (left), with the fixture filter (middle), and covered by aluminum foil (dark control, right). Note that the filter material is solely applied to the lighting fixture. Images were captured using a D65 illuminant.

across between 260 and 500 nm, hence identifying a mixed mechanism. The filters are shown to scatter in the UVB, UVA, and blue-visible regions, reflect in the blue-visible, and absorb in the lower UVC region. TEM and EDS analysis identified well-dispersed nanosized domains (enriched with Al, Si, and O) with the introduction of PCR material. It is likely that the interface of these domains with recycled content is responsible for the scattering behavior.

The efficacy of light reduction from the filters and its influence on light induced degradation of delicatessen rare roast beef in retail display conditions were quantified. Under filtered conditions, no distinguishable difference in roast beef color was observed (both quantitative colorimetric analysis and visual inspection) between the filtered light and the no light control for up to 120 h of exposure time. In contrast, roast beef specimens under non-filtered light reached the maximum color change value of the filtered samples (ΔE ~3.7) ~100 h of exposure time earlier. Retention of meat color was attributed to increased reflection and scattering of the light filter in the visible blue region (445–480 nm), which inhibits metmyoglobin production. With the application of the light filtering technology identified in this study, the perceived quality and freshness of light sensitive delicatessen meats such as rare roast beef can be maintained, extending customer acceptability and marketability.

The significance of this study is not limited to food preservation. The new instrumentation designed to measure optical performance of light filtering film can be broadly applied to many other materials. Furthermore, the sustainable filter technology has the potential to significantly improve color retention of light sensitive foods, reducing overall food waste and providing economic and environmental benefits to a population where food insecurity is highly prevalent.

Data statement

All raw data sets can be obtained from the corresponding author upon request.

Declaration of Competing Interest

Drs. Curtzwiler and Vorst are co-inventors of patent US 10,316,183 B2 “Method for optimizing plastic compositions used in packaging to increase shelf-life of perishable products and a system thereof” which is assigned to Iowa State University Research Foundation and Cal Poly Corporation. Drs. Curtzwiler and Vorst are both employees of Iowa State University.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.susmat.2020.e00193.

References

[1] P. He, L. Chen, L. Shao, H. Zhang, F. Lu, Municipal solid waste (MSW) landfill: a source of microplastics? -evidence of microplastics in landfill leachate, Water Res. 151 (2019) 38–45, https://doi.org/10.1016/j.watres.2019.04.060.
[2] S. Sharuddin, F. Abnisa, W.W. Daud, M.K. Arauda, A review on pyrolysis of plastic wastes, Energy Convers. 115 (2016) 308–326, https://doi.org/10.1016/j.enconman.2016.02.037.
[3] G. Curtzwiler, E.B. Williams, E. Hurban, J. Greene, K. Vorst, Certification markers for empirical quantification of post-consumer recycled content in extruded polyethylene film, Polym. Test. 65 (2018) 103–110, https://doi.org/10.1016/j.polymertesting.2017.11.015.
[4] G. Curtzwiler, E. Williams, A. Maples, N. Davis, T. Bahns, J.E.D. Leon, K. Vorst, Ultraviolet protection of recycled polyethylene terephthalate, J. Appl. Polym. 134 (2017) 45181–45188, https://doi.org/10.1002/app.45181.
[5] G. Curtzwiler, E.B. Williams, K. Vorst, Multivariable Regression Analysis for Empirical Quantification of Post-Consumer Recycled Content in Extruded Polyethylene Film, Society of Plastics EngineersHouston, TX, 2018.
[6] G. Curtzwiler, K. Vorst, Methods of Optimizing Polymer Composition for Sustainable Light Filters and Protectors in Retail Display Case Applications and Methods Thereof, Iowa State University, Iowa State University, Ames, IA, 2018.
[7] K. Vorst, W. Brown, J. Danes, G. Curtzwiler, in: Iowa State UniversityAmes, IA (Ed.), Method for Optimizing Plastic Compositions Used in Packaging to Increase Shelf-Life of Perishable Products and a System Thereof, 2017.
[8] N. Bohner, K. Rieblinger, Impact of different visible light spectra on oxygen absorption and surface discoloration of bologna sausage, Meat Sci. 121 (2016) 207–209, https://doi.org/10.1016/j.meatsci.2016.06.019.
[9] N. Bohner, F. Hosl, K. Rievlinger, W. Danzel, Effect of retail display illumination and headspace oxygen concentration on cured boiled sausages, Food Packag. Shelf Life 1 (2014) 131–139, https://doi.org/10.1016/j.fpsl.2014.04.003.
[10] K.S. Steele, M.J. Weber, E.A.E. Boyle, M.C. Hunt, A.S. Lobaton-Sulabo, C. Cundith, Y.H. Hiebert, T.L. Roenbaugh, K.A. Abrolat, J.M. Attey, S.D. Clark, D.E. Johnson, Shelf life of fresh meat products under LED or fluorescent lighting, Meat Sci. 117 (2016) 75–84, https://doi.org/10.1016/j.meatsci.2016.02.032.
[11] The Color of Meat and Poultry. , United States Department of Agriculture, USDA.gov, 2013.
[12] S. Eckhouse, U.S. Food Waste Challenge, United States Department of Agriculture, USDA.gov, 2018.
[13] J. Parfitt, Food waste within food supply chains: quantification and potential for change to 2050, Philos. Trans. R. Soc. Lond. Ser. B Biol. Sci. 365 (2010) 3065–3081.
[14] G. Tewari, D.S. Jayas, L.E. Jeremiah, R.A. Holley, Prevention of transient discoloration of beef, J. Food Sci. 66 (2006) 506–510, https://doi.org/10.1111/j1365-2621.2001.tb16140.x.
[15] G.H. Zhou, X.L. Xu, Y. Liu, Preservation technologies for fresh meat: a review, Meat Sci. 86 (2010) 119–128, https://doi.org/10.1016/j.meatsci.2010.04.033.
[16] S.P. Suman, P. Joseph, Myoglobin chemistry and meat color, Annu. Rev. Food Sci. Technol. 4 (2013) 79–99, https://doi.org/10.1146/annurev-food-030212-182623.
[17] D.B. MacDougall, Changes in the colour and opacity of meat, Food Chem. 9 (1982) 75–88, https://doi.org/10.1016/0308-8146(82)90070-X.
[18] M. Renerre, Factors involved in the discoloration of beef meat, Int. J. Food Sci. Technol. 25 (1990) 613–630, https://doi.org/10.1111/j1365-2621.1990.tb01123.x.
[19] D.E. Hood, E.B. Riordan, Discolouration in pre-packaged beef: measurement by reflectance spectrophotometry and shopper discrimination, Int. J. Food Sci. Technol. 8 (1973) 333–343, https://doi.org/10.1111/j1365-2621.1973.tb01721.x.
[20] Q. Zia, R. Androsch, H.J. Radusch, E. Ingoliç, Crystal morphology of rapidly cooled isotactic polypropylene: a comparative study by TEM and AFM, Polym. Bull. 60 (2008) 289–297, https://doi.org/10.1007/s00289-008-0908-8.
[21] W.N. Tapp, J.W.S. Yancey, J.K. Apple, How is the instrumental color of meat measured? Meat Sci. 89 (2011) 1–5, https://doi.org/10.1016/j.meatsci.2010.11.021.
[22] A. International, ASTM E1346–06 Standard Test Method for Color and Color-Difference Measurement by Tristimulus Colorimetry, ASTM International, West Conshocken, PA, 2015.
[23] A. International, ASTM D2244–16 Standard Practice for Calculation of Color Tolerances and Color Differences from Instrumentally Measured Color Coordinates, ASTM International, West Conshocken, PA, 2016.
[24] W. Mokrycki, M. Tatol, Color difference Delta E- A survey, Mach. Graph. Vis., 20, 2011 383–411.
[25] A. Larena, G. Pinto, The effect of crystallinity on the light scattering of regenerated cellulose tubular films, Polym. Eng. Sci. 35 (1995) 1155–1160, https://doi.org/10.1002/pen.760351405.
[26] G. Curtzwiler, M. Schweitzer, Y. Li, S. Jiang, K. Vorst, Mixed post-consumer recycled polyolefins as a property tuning material for virgin polypropylene, J. Clean. Prod. 239 (2019), 117978. https://doi.org/10.1016/j.jclepro.2019.117978.
[27] S. Chong, G.T. Pan, M. Khalid, T.C.K. Yang, S.T. Hung, C.M. Huang, Physical characterization and pre-assessment of recycled high-density polyethyene as 3D printing material, J. Polym. Environ. 25 (2017) 136–145, https://doi.org/10.1007/s10924-016-0793-4.
[28] M.E. Grigore, Methods of recycling, properties and applications of recycled thermoplastic polymers, Recycling 2 (2017) 24–35, https://doi.org/10.3390/recycling2040024.
[29] M. Si, T. Araki, H. Ade, A.L.D. Kilcoyne, R. Fischer, J.C. Sokolov, Compatibilizing bulk polymer blends by using Organoclays, Macromolecules 39 (2006) 4793–4801, https://doi.org/10.1021/ma060125.
[30] E. Olson, Y. Li, F.Y. Lin, A. Miller, F. Liu, A. Tsyrenova, D. Palm, G. Curtzwiler, K. Vorst, E. Cochran, S. Jiang, Thin biobased transparent UV-blocking coating enabled by

nanoparticle self-assembly, ACS Appl. Mater. Interfaces 11 (2019) 24552–24559, https://doi.org/10.1021/acsami.9b05383.

[31] S. Jiang, A.V. Dyk, A. Maurice, J. Bohling, D. Fasano, S. Brownell, Design colloidal particle morphology and self-assembly for coating applications, Chem. Soc. Rev. 46 (2017) 3792–3807, https://doi.org/10.1039/C6CS00807K.

[32] S.J. Millar, B.W. Moss, M.H. Stevenson, Some observations on the absorption spectra of various myoglobin derivatives found in meat, Meat Sci. 42 (1996) 277–288, https://doi.org/10.1016/0309-1740(94)00045-x.

[33] C. Faustman, R.G. Cassens, The biochemical basis for discoloration in fresh meat: a review, J. Muscle Foods 1 (1990) 217–243, https://doi.org/10.1111/j1745-4573.1990.tb00366.x.