Exposure to light-emitting diodes may be more damaging to the sensory properties of fat-free milk than exposure to fluorescent light

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ABSTRACT

Light exposure can damage the sensory properties of milk, leading to adverse consumer responses. This is presumed to be through the action of photosensitive compounds such as riboflavin, present in milk and capable of releasing energy when irradiated, leading to damage of proteins and fats in the milk. Light-emitting diode (LED) lighting is assumed to be less damaging to milk due to lower inherent power consumption. In this study, fat-free milk was exposed to LED and fluorescent light at 2,000 lx to compare the sensory thresholds of exposure, the flavor profile of milk produced by these exposures, and resultant consumer acceptance of the samples. Additionally, the effectiveness of light-protective packaging and supplementation with antioxidants was evaluated. The sensory threshold from LED exposure was no longer than from fluorescence, whereas with antioxidants (tocopherols and ascorbic acid), the majority of the panelists failed to discriminate milk exposed to LED light even at 48 h of exposure. Trained panelists described light-exposed milk as significantly higher in cardboard, old oil, and plastic, with LED exposure resulting in a marginally more plastic aroma, and fluorescent marginally more cardboard. Consumers reported higher liking for fluorescent-exposed samples versus those exposed to LED. The antioxidant-supplemented samples, and those exposed to LED light engineered to eliminate wavelengths below 480 nm (thus most of riboflavin's absorption peaks), resulted in significantly higher old oil aroma; however, the former received higher liking scores than LED-exposed samples. Light-protective packaging offered near-complete protection from LED exposure, with a similar flavor profile as unexposed milk, and the best liking scores of any treatment. Nevertheless, consumers disliked its appearance, due to unfamiliarity, suggesting some consumer education may be needed if this were to be an efficient protective strategy.

Key words: fluid milk, sensory, consumer, hedonic, light, light-emitting diode

INTRODUCTION

Americans are not fulfilling their daily recommended intake of dairy products (Stewart et al., 2013), partly due to a decrease in fluid milk consumption. Milk flavor and nutritional content are affected by light. This process begins with riboflavin, porphyrins, chlorins, and other photosensitive components (Wold et al., 2005), once activated, producing singlet oxygen that can react with proteins, vitamins, and lipids (Choe et al., 2005), leading to sensory defects in the milk. The off-flavors generated are mainly attributed to AA and UFA oxidation, forming methionine sulfoxide, dimethyl disulfide, and various aldehydes and ketones (Jung et al., 1998; Min and Boff, 2002; van Aardt et al., 2005).

Light-emitting diode (LED) light usage in retail stores is increasing, but some disagreement is present about the details of the sensory effects of LED on milk. Brotherson et al. (2016) found that fluorescent (at 2,200 lx) compared with LED light (at 4,000 lx) had faster and higher production of off-flavor-generating compounds in 1% milk. In sensory testing, a more complex story emerged. At 12 h, the trained panel detected a bigger decrease in cooked sweet in the LED sample, with a bigger increase in butterscotch and cardboard in the LED samples. However, at 24 h, the majority of the more extreme sensory changes were in the LED sample, with lower milk fat, alongside a higher perception of cardboard in the LED-exposed samples. It should be noted plastic was 0.5 units higher in LED than fluorescent at 24 h, versus only 0.1 units higher in fluorescent at 12 h; thus, presumably we can assume from this result that LED lights are more damaging to milk over long exposure times. Although consumers reported higher liking for the 12-h-exposed LED samples versus fluorescent, no differences in consumer response were reported at 24 h of exposure.

On the other hand, Martin et al. (2016) demonstrated that consumers robustly reject LED-exposed milk (at 1,200 lx), particularly if fat free. When evaluating

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several samples fresh or near code, light exposed or not, consumers rated those exposed to light as less liked than even those approaching code, as long as they were not exposed to light. This came with corresponding increases in plastic aroma in trained panel results. Consequently, it is necessary to characterize and contrast the sensory effect of LED and fluorescent light on fat-free milk (De Jesus and Dando, 2016), and moreover to evaluate possible protective strategies to safeguard milk quality. It is reasonable that light damage favors AA damage, rather than lipid oxidation, in fat-free milk, thus resulting in a differing pattern of sensory damage. Methionine for instance, which breaks down readily in the presence of light and riboflavin (Bradley and Min, 1992), can form multiple species linked to light-activated flavor (Finley and Shipe, 1971).

Protective packaging materials, light wavelength tailoring, and antioxidant supplementation have been studied as possible interventions to prevent milk off-flavors from developing during light exposure. Potts et al. (2017) exposed milk for 4 h to LED and fluorescent light in high-density polyethylene (HDPE) and polyethylene terephthalate (PET) packages with and without TiO₂. Consumers' overall liking did not decrease in any LED condition, only decreasing for the fluorescent light conditions, with translucent materials offering some protection. In another approach, a mixture of tocopherol and ascorbic acid was able to avoid off-flavor development after 10 h of fluorescent light exposure (van Aardt et al., 2005), with oxidation presumably mitigated due to antioxidants reacting with singlet oxygen, or protecting photosensitive compounds (Hall et al., 2010).

The purpose of this study was (1) to determine the minimum duration of exposure to fluorescent and LED light in fat-free milk, and to evaluate the efficacy of antioxidant enrichment, (2) to compare the flavor profile via descriptive sensory of fat-free milk exposed to LED and fluorescent light, as well as determine the effectiveness of protective measures in milk exposed to LED, and (3) to characterize consumer acceptance for all these conditions.

MATERIALS AND METHODS

All procedures in this report were approved by the Cornell Institutional Review Board for testing with human subjects. Testing consisted of 3 phases of testing, each with a different design and panel. Full details of each session are given below. In the first, samples were tested for the threshold time of exposure sufficient for panelists to notice a difference between nonexposed and exposed samples, for milk exposed to LED, to fluorescent, and to LED with antioxidant enrichment. In the

second phase, descriptive analysis examined samples over multiple sessions, exposed to LED and fluorescent, as well as a control, samples enriched with antioxidants and the same samples later exposed to LED, a sample exposed to LED light lacking riboflavin excitation bands, and samples exposed to LED while in light-protective packaging. In the final phase, consumers assessed their liking for the same samples as phase 2.

Sensory Threshold Testing

Three sessions were scheduled to test the minimum duration of exposure to fluorescent light; to LED light (hereafter referred to as the sensory threshold of light exposure); and to exposure to LED with antioxidants. The sessions took place 1 wk apart, from a separate lot of fresh milk each time. In each part of the study, fat-free milk was purchased from the Cornell dairy plant, with each day of testing using samples from the same production run. Milk was HTST pasteurized at 173°F (78.3°C) for 22 s. Control milk bottles were wrapped in aluminum foil after processing and were not exposed to light. All samples were stored at 4°C in high-density polyethylene half-gallon containers with lids. Bottles were not open until pouring and had minimal headspace. Samples were exposed at 2,000 ± 100 lx to either LED (Zhejiang Yankon Group Co. Ltd., China) or fluorescent (Lab Supplies Co. Inc., Hicksville, NY) light. Rigs were custom made, and each bottle was positioned using a light meter so the light-facing edge was at a position corresponding to 2,000 lx. For the antioxidant treatment, food-grade mixed tocopherols and L-ascorbic acid were purchased from Sigma-Aldrich (St. Louis, MO) and added at 0.025% tocopherols and 0.025% L-ascorbic acid. Thirty-milliliter samples were poured into 5-oz plastic cups with plastic lids. An ascending exposure forced-choice method was used. A 3 alternative forced choice threshold test with 8 steps (0.5, 1, 2, 4, 8, 12, 24, and 48 h) was used. Participants were presented with sets of 3 samples, 2 of which were controls and 1 of which was the light-treated sample. Panelists were instructed to identify the odd sample. Participants evaluated the sets starting with the least exposed sample (1 h) and ending with the most exposed (48 h). Samples were presented at 4 to 6°C. Each session was conducted on a separate day, with panelists recruited from Cornell University's staff, student, and faculty population. Participants received a \$5 compensation for each session and a \$10 bonus if they attended all 3 sessions. Fifty-six panelists attended the fluorescent session, 67 panelists the LED session, and 66 panelists the LED with antioxidants session.

Participants performed the test in separate sensory booths on computers using RedJade sensory evalua-

Table 1. Descriptive analysis attributes and references¹

Item	Reference
Orthonasal aroma attribute	
Cream	Upstate heavy cream (Upstate Niagara, Buffalo, NY)
Old oil	Unsalted Premium crackers, stale (Wegmans Inc., Rochester, NY)
Sulfur	Wegmans eggs, boiled and mashed (Wegmans Inc.)
Plastic	Clear mildew-proof shower curtain
Mushroom	Chopped crimini mushroom (Wegmans Inc.)
Flavor attribute	
Cooked	Parmalat UHT milk (Parmalat SpA, Collecchio, Italy)
Butter	ICB Inc. spray margarine (Unilever, London, UK)
Sweet	Lactaid 100% (HP Hood, Lynnfield, MA) and Cornell Dairy skim milk (50:50)
Aftertaste attribute	
Cardboard	Byrne Dairy skim milk (Byrne Dairy, Syracuse, NY)
Sweet	Lactaid 100% and Cornell Dairy 2% milk (50:50)
Metallic	Ferrous sulfate heptahydrate, 0.01 g/L of spring water (Sigma-Aldrich, St. Louis, MO)
Sour	Upstate Farms buttermilk (Upstate Niagara)
Bitter	Caffeine, 2 g/L of spring water (Sigma-Aldrich)
Appearance attribute	
Whiteness	Flagship, WBM-20100, 92 brightness paper (WB Mason, Syracuse, NY)
Visual thickness	Continuum of fat in dairy products
Texture attribute	
Oral thickness	Continuum of fat in dairy products

¹Continuum of dairy products were samples of heavy cream, heavy cream, and 2% milk (50:50), heavy cream and 2% milk (25:75), 2% milk, skim milk, and skim milk with water (75:15).

tion software (Tragon Corp., Deerfield, IL), and were asked to expectorate samples and clean their palate with water after tasting each sample. The presentation order was randomized for each panelist. The sensory threshold exposure time for each treatment was calculated as the geometric mean of exposure time of correct judgment from each individual panelist. The individual thresholds were calculated as the geometric mean of the last incorrect judgement and the value at which all higher concentrations were correct, acknowledging that a panelist's actual threshold would lie between these 2 points.

Descriptive Analysis

Descriptive sensory evaluations were performed by a trained panel on 9 fat-free milk samples. Training consisted of ballot training, followed by identification of attributes in engineered samples, then moving to rating of the attributes in physical references, and in spiked dairy samples. Multiple intensities of each attribute were scaled for intensity (10-point line scale) with multiple attributes for each sample in later sessions. Training was performed using Compusense At-Hand feedback calibration on iPad minis; thus, panelists received immediate feedback after every rating. During testing, each sample was presented in duplicate and panelists rated a total of 6 samples per session, over 3 sessions on separate days, with a control in each session. Controls did not differ between days, and thus are presented as

an average. A total of 12 panelists participated and were trained for a total of 24 h each using Feedback Calibration (Findlay et al., 2007) to allow for faster training times. Attributes were divided into 5 categories: aroma, appearance, flavor, aftertaste, and texture. Old oil, plastic aroma, and cardboard taste are often associated with light exposure; however, several general attributes related to milk were also assessed (see Table 1). For training and testing, panelists used Compusense Cloud sensory evaluation software (Compusense Inc., Guelph, Ontario, Canada). Unstructured 10-point line scales were used to rate all attributes during the training and testing periods.

Light exposure was as above, but also included an engineered LED light designed to cut out all wavelengths below 480 nm (and thus the majority of riboflavin excitation, referred to henceforth as **Ribo LED**), at 4,669 K with a dominant wavelength of 580 nm, centroid wavelength of 550 nm (EnviroLux Energy Systems, Vancouver, WA). Milk was exposed in all descriptive testing for 24 h at an intensity of $2,000 \pm 100$ lx. Milk enriched with antioxidants was also evaluated with and without LED exposure, as well as a sample exposed to LED while in a light-protective PET bottle (ColorMatrix Lactra SX, ColorMatrix, Knowsley, UK, referred to throughout as light protective packaging). Samples were poured under low lighting in 5-oz plastic cups with plastic lids. Panelists were instructed to inspect and smell samples, and evaluate visual and aroma attributes. After this, they tasted the sample

and rated flavor attributes. Finally, they resampled and rated aftertaste and mouthfeel. Enforced breaks were included during the test to minimize fatigue, where panelists were instructed to cleanse their palates with crackers and water. Sample order was randomized for each panelist and repetition. Participants received \$10 compensation for each hour of training and testing.

Consumer Analysis

Samples were obtained and prepared as above (aside from now a single control instead of 3 were evaluated). A total of 130 participants recruited from Cornell University's staff, faculty, and student population completed the test. Consumers were selected with the following restrictions: no milk allergy or intolerance, no taste or smell disorders, and consumers of fat-free milk. Each panelist received \$5 compensation.

Panelists first inspected images of 7 milk bottles, each showing a treatment condition: milk under fluorescent light, under LED (2 duplicates, representing before and after exposure), under Ribo-LED lighting, in protective packaging, and with antioxidants under LED (2 duplicates, representing before and after exposure). The pictures were presented in a randomized order. After each picture the respondent was asked to rate their overall liking of the appearance of the product on the 9-point scale, from like extremely (9) to dislike extremely (1). Then, panelists tasted 7 milk samples in a randomized complete block design and evaluated each sample for liking (overall, appearance, aroma, and flavor), on the scale above. At the end of the test, respondents answered demographic and usage questions. Each session lasted approximately 35 min.

Statistical Analysis

Statistical analysis was conducted using Graphpad Prism (GraphPad Software Inc., San Diego, CA) and Addinsoft XLSTAT (Addinsoft, Paris, France). One-way repeated measures ANOVA calculated if the treatments differed, with post-hoc Tukey's tests examining each pair. Principal component analysis (Pearson n), cluster analysis (Ward's method with Euclidean distance), and preference mapping were performed to understand the relationships among the sensory attributes and consumers' liking for the samples.

RESULTS

Sensory Thresholds

The sensory threshold for detecting differences in fluorescent light-exposed milk was 12 h (Figure 1). In

contrast, the threshold for detecting differences in LED-exposed milk was 9 h, meaning that LED offered no improvement in the exposure time required for untrained panelists to detect off-flavors in light-exposed milk. The addition of antioxidants resulted in significantly fewer panelists discriminating the LED-exposed sample from controls ($P < 0.001$), with the group sensory threshold over our maximum 48-h time point. It should be noted that the control samples for this test also contained antioxidants, and thus despite panelists being unable to discern exposed samples from shielded, the panelists may have found this formulation inherently less pleasant; however, this was not evaluated.

Descriptive Analysis

When examining all 16 attributes, only those associated with light-exposed flavors differed between the samples (Clark et al., 2009; Martin et al., 2016; Figure 2). Old oil aroma was significantly different between treatments (repeated measures ANOVA, $P < 0.001$), being higher in the Ribo-LED-exposed milk than control, as well as packaging treatment. Moreover, antioxidant supplementation followed by light exposure also increased old oil percept when compared with the control sample ($P < 0.05$). Plastic aroma was significantly higher in LED, Ribo-LED, and the antioxidant-supplemented milk compared with the control sample. Finally, in Ribo-LED and antioxidant-exposed milk, cardboard aftertaste was significantly higher when compared with the control. Fluorescent samples also showed higher cardboard aftertaste, but this difference did not reach significance.

Figure 1. Results from threshold testing with ascending duration of light exposure. The y-axis denotes percentage of panel successfully discriminating the odd sample, and the x-axis denotes light-exposure time. Light-emitting diode (LED)-exposed samples (squares with dashed line) showed no improvement in threshold from fluorescent (Fluo) exposed (circles with solid line). Adding 0.025% mixed tocopherols and 0.025% L-ascorbic acid (triangles with dotted line) significantly extended thresholds of LED-exposed milk (all at 2,000 lx). Differing letters indicate a significant difference at $P < 0.05$.

Figure 2. Results of descriptive testing. Of all attributes tested, only old oil aroma (A, $P < 0.001$), plastic aroma (B, $P = 0.047$), and cardboard aftertaste (C, $P < 0.001$) differed in light-exposed milk (repeated measures ANOVA). Bars show mean and SEM. The y-axis denotes sensory intensity on a 10-point scale. LED = light-emitting diode; Fluo = fluorescent; Ribo = riboflavin; Antiox = antioxidant. Differing letters indicate a significant difference at $P < 0.05$.

The PET packaging resulted in very similar ratings to controls, protecting milk from LED light damage for 24 h, and resulting in sensory properties similar to those from unexposed samples in all attributes.

Consumer Testing

Flavor, aroma, and overall liking differed between treatments (Table 2, Figure 3A, all $P < 0.001$). Consumers reported a higher liking of the control sample and for milk exposed while in protective packaging (Figure 3A). In accordance with the descriptive panel, consumers liked the control and the light-protective packaging equally. Interestingly, however, the samples exposed to LED light at an identical lux and duration were significantly less liked than samples exposed to

fluorescent light. Likewise, samples exposed to LED after antioxidant enrichment were still less liked than those enriched and not exposed. Finally, light engines (custom LED boards) lacking wavelengths below 480 nm, thus eliminating the majority of riboflavin excitation, were interestingly liked the least of all samples. Consumers also rated the appearance of the containers themselves, rating either standard HDPE containing fat-free milk, and lit by fluorescent/LED/Ribo-LED, or samples supplemented with antioxidants lit by LED, or lastly the light-protective PET bottle lit by LED. Package appearance liking significantly differed between treatments (repeated measures ANOVA, $P < 0.001$). The most liked samples were the sample illuminated by LED lacking riboflavin bands, and the sample lit with fluorescent lighting (Figure 3B). Antioxidant

Table 2. Table denoting consumer panel liking scores¹

Item	Control	Packaging	Fluo	LED	Ribo LED	Antiox control	Antiox LED
Appearance liking	5.83 ^A	5.79 ^A	5.80 ^A	5.93 ^A	5.75 ^A	5.68 ^A	5.85 ^A
Aroma liking	5.56 ^A	5.72 ^A	4.59 ^B	4.49 ^B	3.82 ^C	4.83 ^B	4.61 ^B
Flavor liking	5.96 ^A	6.26 ^A	4.99 ^B	4.65 ^B	4.04 ^C	5.01 ^B	4.35 ^C

^{A-C}Superscript letters indicate significant difference in post-hoc Tukey's test defined as $P < 0.05$.
¹All categories are rated on a 9-point scale, with higher scores denoting a higher degree of liking. LED = light-emitting diode; Fluo = fluorescent; Ribo = riboflavin; Antiox = antioxidant.

Figure 3. (A) Overall liking. (B) Liking of appearance of containers. Vertical axis represents liking on 9-point hedonic scale, with bars denoting mean and SEM. Letters (A–D) represent statistical significance between treatments at $P < 0.05$, post-hoc Tukey's test. LED = light-emitting diode; Fluo = fluorescent; Ribo = riboflavin; Antiox = antioxidant.

supplementation resulted in a less liked appearance than without, likely due to some color imparted by the enrichment. Despite the fact that milk in protective packaging obtained the highest score for the liking of the sample itself, consumers expressed discomfort about this container, giving it the lowest liking score for appearance of the package itself. When asked for open-ended comments on reasons for disliking the sample,

panelists most often cited the unfamiliarity of the package ($n = 24$) and that they could not see the product itself inside the container ($n = 12$).

Multidimensional Analysis

Principal component analysis was performed to visualize the relationships between both samples and attributes. The first 2 components accounted for over 80% of the variation, mainly representing (1) cardboard, whiteness, plastic, sweet aftertaste, cream, and oral thickness, and (2) sulfur and old oil. As the samples were evaluated over 3 d to ensure the milk's sensory properties did not change between testing sessions merely due to storage, a control sample was evaluated each day. When localizing the samples in the multidimensional space, the control sample and the sample in light-protective packaging clustered close together, and were low in factor 2 while being negative in factor 1, whereas Ribo-LED and the antioxidant control were notably high in factor 1 (Figure 4). Antioxidant-enriched and LED-exposed milk was high in factor 2, whereas the primary difference between fluorescent and LED-exposed samples in the multidimensional space seemed to be higher scores for LED-exposed samples in factor 2.

Cluster analysis identified 2 main groups of consumers. The first cluster consisted of 27 consumers, liked LED over fluorescent-exposed milk, whereas the remaining consumers ($n = 103$) liked fluorescent-exposed milk over LED. Both segments still liked control and packaging samples over all other samples; however, group 1 (LED likers) liked higher "sulfur/old oil" and a lower level of factor 2, whereas group 2 (fluorescent likers) liked lower "sulfur/old oil." Most of the consumers preferred to drink 2% and whole milk given the choice, despite reporting consuming fat-free milk (Figure 5). However, interestingly, a statistical overrepresentation of consumers that preferred fat-free milk also liked the fluorescent-exposed milk more than LED-exposed milk.

DISCUSSION

LED Offers No Protection Over Fluorescent from Light-Induced Sensory Off-Notes, or Reduced Consumer Liking in Fat-Free Milk

The threshold for detecting fluorescent light-exposed milk was 12 h. Although this was not in agreement with previous findings noting shorter thresholds (Heer et al., 1995; Chapman et al., 2002), it is important to note that both the method and the milk fat content used in our study were different from those previously. Chapman et al. (2002) used the semi-ascending paired difference

method; in this method panelists are given a reference and 3 samples, then they are asked to compare each sample to the reference and rate the intensity of the difference (Chapman et al., 2002); panelists have better sensitivity in detecting differences when they have been provided a reference. Although the assumption is that what the panelists were detecting was off-flavor generation arising from light damage, as the panelists are only instructed to identify the odd sample, we do not know whether the flavor formed with light was positive or negative in nature in the threshold section of this study. Additionally, whereas it is possible that the difference in panel constituents between sessions may have resulted in a slightly different sensitivity to any off-flavors generated in the light-exposed samples, no systematic bias was present between populations, with the majority taking part in all 3 sessions.

The LED and fluorescent light both exhibited damaging effects to milk flavor. The LED lighting's off-flavor detection threshold was shorter (thus detected sooner, although not statistically). Moreover, the flavor profile between these light treatments differed.

LED samples were characterized by a higher plastic aroma, whereas fluorescent samples presented a higher cardboard aftertaste. Consumers' overall, flavor and aroma liking ratings were higher when milk was exposed to fluorescent light compared with that of milk exposed to LED lighting. Thus in general, LED lighting appeared more damaging to the hedonic properties of fat-free milk, and caused more off-flavors than did fluorescent. While 2 recent studies (Brothersen et al., 2016; Potts et al., 2017) hinted that LED may not be as damaging as fluorescent, differences in results may have been due to their tests taking place in 1 and 2% milk, respectively. When testing light damage in fat free versus 2% milk, it was clear that the presence of fat offered some protection from the influence of light (Martin et al., 2016). This would suggest that fat-free milk may be fundamentally more susceptible to light damage than milk with a higher fat content. This may be in part at least due to riboflavin's superior stability in milk containing fat versus fat-free milk (Gaylord et al., 1986). We would speculate that those preferring fat-free milk may thus be more comfortable with

Figure 4. Preference map, where x- and y-axes represent first 2 factors of principal component analysis attributing to 65 and 15% of variance in the data set. Solid lines and circles represent projection of original attributes through the space, with squares representing the samples in multidimensional space. Triangles and lines represent liking vectors for 2 segments within consumers, labeled 1 and 2. Antiox = antioxidant; LED = light-emitting diode.

Figure 5. (A) Two segments of fat-free milk drinkers are evident from analysis, dissimilarity on y-axis; consumers closer on the dendrogram represent similar responses. (B) Consumers who preferred fat-free, 2%, and whole milk as a percentage of the segment. Significantly more light-emitting diode (LED) likers were fat-free milk drinkers ($P < 0.01$, chi-squared test; $**P < 0.01$). Fluo = fluorescent light.

some level of light damage, as is likely occurring in our segmentation analysis (Figure 5). Recent research has noted the importance of examining the nontrivial contribution of a consumer's preferred level of fat in milk (Bakke et al., 2016). Although all of our consumers did report consuming fat-free milk, it was clear when they were asked their preferred type of milk that some were consuming fat-free milk without truly preferring it, likely for health concerns. As a consumer may be more discerning of either flavor attributes or hedonic differences in their preferred milk type (McCarthy et

al., 2017), a more sensitive approach may have been to recruit only those who truly preferred fat-free milk. Nonetheless, recruiting multiple segments revealed that those preferring fat-free milk may be less tolerant of damage arising from LED than those preferring other categories (Figure 5).

Light Damage in Fat-Free Milk Is Due to More Than Just Riboflavin Activation

Studies have previously examined the influence of irradiation wavelength on the sensory properties of milk and other dairy products (Hoskin and Dimick, 1979; Wold et al., 2006; Webster et al., 2009). The influence of light exposure from LED lacking wavelengths below 480 nm was intended to test the hypothesis that eliminating riboflavin activation would preserve the sensory properties of milk. In fact, these samples were rated lower by the consumer panel, and saw higher levels of off-flavor generation than standard LED. Milk exposed to this light presented higher old oil aroma, plastic aroma, and cardboard aftertaste than all other treatments. Several additional photosensitive compounds are present in dairy products, aside from riboflavin. These would include porphyrins and chlorophyll, equally capable of transferring energy to milk in the form of free electrons (Wold et al., 2005; Intawiwat et al., 2010). Whereas eliminating wavelengths below 480 nm would mediate some of the excitation of species at low wavelengths, ensuring an equal brightness of light would mean longer wavelengths were in fact stronger in this scheme, and thus any species excited above 480 nm may be more intensely excited, thus becoming more damaging. As chlorophyll A excites strongly at 650 to 680 nm (Makarska-Bialokoz, 2012), this would represent a potential mechanism for sensory damage we observed with the Ribo-LED treatment. Although our study was not designed to examine the influence of the various photosensitizers present in milk specifically, this would certainly represent an interesting area for further examination.

Light-Protective Packaging May Be the Most Effective Approach in Protecting Milk from Photo-Induced Sensory Damage

As discussed above, merely eliminating riboflavin absorption bands below 480 nm was not an effective strategy in preventing off-flavor generation. Antioxidant supplementation had at least some protective effect against milk oxidation. Sensory thresholds demonstrated that this strategy mitigated off-flavor development and color changes in milk respectively. However, unlike the results of van Aardt et al. (2005), adding 0.025%

α -tocopherol and 0.025% ascorbic acid did result in some sensory differences detected by both trained and consumer panels irrespective of light-exposure, modifying milk flavor in a negative manner. Milk samples with antioxidants presented higher old oil aroma, probably from tocopherols. This likely led to consumers not liking these samples as much as controls.

Many studies have noted the importance of packaging in safeguarding milk quality from light damage (see review by Coleman et al., 1976; Bradley, 1980; Rysstad et al., 1998). Some form of protective packaging is likely the future of milk protection (Moyssiadi et al., 2004; Mestdagh et al., 2005; Johnson et al., 2015). In our own studies, light-protective packaging clearly offered the most effective protection from light damage. The flavor profile, as well as consumer response of milk stored in light-protective packaging was very similar to controls. Trained panelists did not detect any off-flavors at all in LED-exposed milk packed in PET bottles. Importantly, these samples received the highest ratings in overall, aroma, and flavor liking when consumers rated them. Although many sensory and consumer studies have examined containers in protecting from light, our study also examined any drop in consumer appeal due to the containers themselves. Interestingly, consumer liking of the appearance of the container was not in agreement with consumer response to the milk's flavor. In fact, consumers robustly rated this package as less liked than any other treatment, flavor notwithstanding. This would suggest that if we concede that light protective packaging is the optimal approach in protecting milk flavor, some education of consumers may be beneficial, to convince them of the packages' utility. As reported previously (White, 1985), only a small number of consumers cited a lack of transparency as an important factor in determining their liking of the package. Alternatively, the majority of criticisms for the packaging were related to its unfamiliarity, suggesting that if such an approach were adopted, the problem would become less important with time, as such packaging became progressively more familiar. As a further alternative, a packaging design more resembling the HDPE package, but with added protective properties could be a solution for this issue. Nonetheless, it is important to note that only a minority of consumers would buy a protective container if it cost just a few cents more (White, 1985).

Both LED and fluorescent light cause damage to the sensory properties of fluid milk. Further research is necessary to understand finer details of the mechanisms by which light-activated flavor is developed, the optimal wavelength spectra to avoid this, and the nutritional losses occurring during exposure. Overall, light-protective

packaging proved to be the optimal approach to avoid light-induced damage to milk; however, either a transparent or more familiar protective package is needed, or consumers will need to be educated to learn to accept this newcomer to the milk aisle.

CONCLUSIONS

Both LED and fluorescent light cause off-flavors in milk. The LED treatment resulted in a shorter threshold, with marginally higher plastic aroma development, and lower liking scores than the fluorescent treatment of equal brightness and duration. Further, minimizing riboflavin excitation did not protect milk as expected, on the contrary appearing to increase off-flavor development likely due to the influence of other photosensitive compounds aside from riboflavin. Antioxidant enrichment offered some protection, but modified milk flavor in other manners. Overall, light-protective packaging materials provided the optimal approach to avoid light-induced damage to milk; however, the appearance of the container was not liked, meaning it would likely not sell well. Thus, either an appearance that better resembles current packaging options or some degree of consumer education may be necessary for such a strategy to succeed. In the future, further research would be valuable to elucidate the mechanisms by which the light-oxidized flavor is developed, the optimal wavelength spectra to avoid this, and the nutritional losses occurring during such an exposure.

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