KVASNÝ PRŮMYSL

Kvasny prumysl (2024) 70: 967–975
https://doi.org/10.18832/kp2024.70.967

Beer Photodegradation in Commercial Bottles: Simultaneous Evaluation by Consumer Sensory Panels and Optical Detection

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Abstract

The impact of light on beer degradation is a well-established phenomenon, leading to development of undesirable flavours or, in severe cases, complete spoilage. This study investigates the extent to which photodegradation is perceptible to beer consumers. Beer samples in commercial bottles were subjected to controlled light exposure to induce defined levels of degradation. The degree of light damage was monitored using both an optical method of tracking changes in absorbance and riboflavin content via HPLC and a sensory evaluation by a lay consumer sensory panel. The findings from the sensory panel were statistically compared with the optical measurement results, highlighting correlations between the sensory perception and quantifiable optical changes.

Keywords: beer; photodegradation; light-struck flavour; riboflavin; absorbance; lay sensory panel; triangle sensory test; HPLC analysis; functional data; regression

1 Introduction

Exposure to light is a well-documented cause of undesirable flavour development and, in extreme cases, spoilage of beer. As early as in 1875, Lintner described the effects of light radiation on beer's quality and taste, referring to the phenomenon of "light-struck flavour" (LSF), also known as "skunk flavour." The compound responsible for this off-flavour is 3-methylbut-2-ene-1-thiol (MBT) (Irwin, 1993). Riboflavin (RF) plays a pivotal role in this process, as it absorbs light in the blue part of the spectrum and transfers excitation energy to isohumulones (Sakuma et al., 1991). This reaction results in the degradation of RF, which causes a reduction in the beer's absorbance in the blue region of the spectrum at approximately 450 nm, directly correlating with the formation of LSF (Gabriel et al., 2022b).

Key factors influencing the rate of beer's light degradation include the intensity and spectral composition of incident light, the concentrations of RF and isohumulones, and the colour of the bottle, which determines the extent of light attenuation through the bottle wall (Gabriel et al., 2022a; Gabriel et al., 2022b). Additionally, the overall composition of the beer, particularly the presence of compounds that interact with excited RF and inhibit energy transfer to isohumulones, may significantly affect its susceptibility to degradation.

Currently, optical damage in beer is typically investigated only in response to complaints regarding off-flavours or odours. Standard procedures do not test beer or its packaging for susceptibility to light damage. Objective and reproducible evaluations require controlled light exposure conditions and precise quantification of the resulting optical damage. This is conventionally achieved through the sensory evaluation by trained expert panels (Irwin, 1993). However,

Research Institute of Brewing and Malting
Published online: 15 December 2024

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the sensory analysis is resource-intensive, requiring skilled professionals, specialized facilities, and well-equipped sensory laboratories.

A routine sensory assessment of multiple samples is further complicated by a rapid saturation and slow recovery of olfactory sensors at higher LSF intensities. Moreover, the intensity of LSF must be evaluated immediately after pouring the beer, as the odour quickly dissipates. These limitations make sensory evaluation impractical for routine operational inspections.

Until recently, it was not possible to assess the degree of optical damage in beer directly within closed packages without opening them. However, beer light degradation is associated with changes in the sample's optical properties. A previous study by Gabriel et al. (2022b) demonstrated that light degradation in beer can be optically monitored within a sealed commercial bottle using the Colorturb device. This device measures the decrease in absorbance at 466 nm (AbsBlue) under defined illumination conditions. The study concluded that the reduction in absorbance at 466 nm highly correlates with RF degradation and the formation of LSF, making it a reliable marker for light-induced degradation processes in beer.

To prepare samples with defined levels of light degradation, we utilized the illumination adapter, which provides uniform spatial and temporal light exposure. The extent of light degradation was controlled by adjusting the exposure time and verified by measuring the decrease in AbsBlue absorbance and RF content.

In this study, we employed a lay sensory panel to evaluate the degree of light degradation in beer. The primary reason for using lay assessors is that most beer consumers are non-experts, making their feedback more reflective of real-world conditions. However, lay panels often exhibit greater variability compared to trained assessors due to their heterogeneity. As Lawless and Heymann (2010) note, up to one-fifth of lay panellists may fail to identify differences and resort to guessing, leading to potentially inconsistent results across panels. Nonetheless, using lay assessors provides insights that are highly relevant for manufacturers, as consumer opinions are ultimately decisive.

The objective of this study is to quantify the extent of light degradation detectable by a lay sensory panel and to compare their findings with two objective measures: the decrease in RF content and the reduction in absorbance at 466 nm (AbsBlue) as described in Gabriel et al. (2022b).

2 Materials and methods

2.1 Beer samples

Pilsner-type beer samples in 0.5 L green bottles were supplied by a local Czech brewery. The bottles were taken directly from the bottling line, immediately wrapped in aluminium foil, and placed in a paper box to protect them from light exposure. Subsequently, they were stored in a dark and cold environment. Each batch consisted of 30 bottles collected sequentially from the bottling line. Filtered and pasteurized beer was used for the experiments. Long-term monitoring of the selected beer confirmed that the oxygen content in the bottles was consistently below 100 ppb.

2.2 Absorbance standard

A yellow tartrazine dye solution was prepared by dissolving 10 mg of tartrazine (dye content ≥85%, Sigma-Aldrich) in 1 L of deionized water. The deionized water, with a conductivity of less than 0.2 µS/cm, was obtained using an Aqual 35 instrument. The absorption spectrum of the tartrazine solution was measured using a single-beam spectrophotometer (Specord 40, Analytik Jena) with a 1 cm cuvette. The solution was then diluted with deionized water to achieve a final absorbance of 0.2 AU at 450 nm.

2.3 Illumination adapter

A specialized adapter was developed to ensure uniform illumination of bottled samples. The adapter comprises a plastic tube lined internally with a strip of light-emitting diodes (LEDs) emitting a wavelength of 450±30 nm, which corresponds to the maximum absorbance of RF. Bottles containing samples are placed inside the tube. The light intensity within the illuminator is temporally and spatially stable, with a variation of less than 0.1%. For further details, refer to Gabriel et al. (2022a).

2.4 HPLC analysis

HPLC analysis was performed using an Ultimate 3000 instrument (Dionex) equipped with a multichannel fluorescence detector. Chromatographic separation was conducted on an Ascentis® Express C18 column (250 mm × 3 mm × 5 µm) with a C18 guard column, maintained at 30 °C, using gradient elution. Mobile phase A consisted of 0.05 M phosphate buffer (K_2HPO_4, KH_2PO_4, pH 7; Lach-Ner, Czech Republic), while mobile phase B was methanol (Sigma-Aldrich). The elution gradient was as follows: 0 min/97% B, 5–15 min linear decrease to 30% B,

15–25 min at 30% B, 25–30 min rapid increase to 97% B, and 30–35 min at 97% B. The total runtime was 35 minutes, with a flow rate of 0.3 mL/min and an injection volume of 5 μL. Riboflavin was detected using an excitation wavelength of 440 nm and an emission wavelength of 520 nm, following the method described by Hucker et al. (2011).

2.5 Absorbance Measurement with the Colorturb device

The Colorturb device was specifically designed and developed to measure changes in colour and turbidity in beverages within commercial packaging, see Gabriel and Sigler (2018). The device accommodates samples in cuvettes or directly in commercial bottles, with volumes ranging from 0.1 L (cuvettes) to 2 L (PET bottles). This design enables to take measurements without opening the packaging. To reduce the influence of the bottle on measurement results, samples are placed in a chamber filled with immersion liquid and subjected to controlled rotation during analysis.

The device utilizes a red-green-blue LED light source, enabling independent absorbance measurements in three distinct wavelength regions, ranging from one to four absorbance units (AU). Colorturb device provides three absorbance values corresponding to the light sources: AbsRed (630 nm), AbsGreen (518 nm), and AbsBlue (466 nm). Additionally, turbidity is measured using a red-light source at detection angles of 90° and 13°–20°.

Measurements at these three wavelengths effectively eliminate the influence of bottle colour on the results, allowing differentiation not only in colour intensity but also in colour hue of the sample. For further details, see Gabriel and Sigler (2018) and Gabriel et al. (2022a). The absorbance measurement at 466 nm is specifically designated as AbsBlue. The Colorturb device has a detection limit of 0.001 AU, with measurement repeatability exceeding 0.005 AU, as reported by Gabriel and Sigler (2018).

Figure 1 *Colorturb device*

2.6 Characterization of bottle properties

Green bottles were selected for light degradation experiments due to their partial transmission of blue light in the spectral range of 420–480 nm, which corresponds to the absorption maximum of RF, thereby enabling light degradation of the sample. Additionally, 0.5 L bottles were chosen as they allow the preparation of up to nine samples for sensory analysis, and their longer geometric optical path enhances the sensitivity of absorbance measurements compared to smaller packaging.

The geometric length of the optical path for the selected bottles was determined using the following procedure. A set of 30 bottles was emptied, cleaned, and filled with distilled water, and their absorbance was measured using Colorturb ($AbsBlue_W$). The bottles were then emptied, filled with a tartrazine dye solution, and measured again using the same device ($AbsBlue_T$). The absorbance of the tartrazine dye solution in each bottle was obtained by subtracting the absorbance values measured for distilled water from those measured for the dye solution.

A precision cylindrical cuvette with a known optical path length of L_C = 6.0 cm was filled with the same tartrazine dye solution, and its absorbance was measured using Colorturb ($AbsBlue_C$). The optical path length of the beam in each bottle, L_B was calculated as the ratio of the absorbance measured in the bottle to that measured in the cuvette (see Equation 1).

$$L_B = \frac{AbsBlue_T - AbsBlue_W}{AbsBlue_C} * L_C \tag{1}$$

The average optical path length L for the set of bottles was calculated as L=5.0±0.1 cm.

2.7 Evaluation of Light Attenuation in Sample Bottles

In the illumination adapter, the intensity of light reaching the sample is determined by the attenuation properties of the bottle walls. To evaluate these transmission properties, 30 bottles were emptied, cleaned, and filled with distilled water. Absorbance measurements were then conducted using the Colorturb device. These measurements facilitated the assessment of how the bottle colour influences the amount of light transmitted to the sample during illumination (Gabriel and Sigler, 2018).

The average wall absorbance of the selected bottles was calculated as 0.773±0.012 AU. Notably, during AbsBlue measurements, light passes through the bottle wall twice.

$$Transmitance[\%] = 100 * 10^{\left(-\frac{AbsBlue}{2}\right)} \tag{2}$$

Using Equation (2), the average transmittance of the bottle was calculated as Transmittance [%] = 41.1±0.5. This indicates that only 41.1% of the incident light at a wavelength of 450 nm penetrates the bottle. The variation in light transmittance among the selected bottles was within 1%. During illumination in the illumination adapter, the intensity of light reaching the sample through the bottle is uniform across all samples, making exposure time the decisive parameter in determining the level of light-induced damage to the sample.

2.8 Sample Selection for Sensory Experiments

For reliable sensory test results, it is crucial to ensure that all samples are sensorially identical before undergoing light degradation and sensory analysis. Despite being taken sequentially from the bottling line and stored under uniform conditions, samples may vary due to factors such as non-standard bottles, leaky caps, or subsequent beer oxidation.

To identify non-standard samples, we used the colour and turbidity measurements performed directly on the Colorturb device. The absorbance of each bottle represents the combined absorbance of the bottle itself and its contents. Deviations from the average absorbance value indicate either a non-standard bottle or non-standard beer. For the set of bottles, the AbsBlue absorbance values were measured, yielding an average value of 2.266±0.021 AU. Each bottle was measured three times, and the mean and standard deviation were calculated. A higher standard deviation in repeated AbsBlue measurements indicated sample non-uniformity. Additionally, turbidity values were recorded, as increased turbidity also signifies a non-standard sample.

Initially, samples with turbidity values exceeding three times the standard deviation of the average were excluded as outliers. Similarly, samples with a standard deviation in repeated AbsBlue measurements greater than three times the standard deviation of the average were excluded. Lastly, samples with AbsBlue values exceeding three times the standard deviation from the mean were also removed. After outlier exclusion, the selected samples had an average AbsBlue value of 2.256±0.012 AU, where the standard deviation of 0.012 AU reflects variability across all bottles, while the standard deviation of repeated measurements for any individual bottle was less than 0.001 AU.

2.9 Optical Method for Assessing the Degree of Light-Induced Degradation in Beer

The degree of light degradation in beer was determined by measuring changes in absorbance directly within the bottle. Light-induced degradation is associated with RF breakdown, leading to absorbance changes near 450 nm, as documented by Pozdrik (2006) and Gabriel et al. (2022b).

The decrease in absorbance reflects the loss of RF due to its decomposition during the light-induced degradation of beer, which directly correlates with a reduction in sample absorbance. Gabriel et al. (2022a) demonstrated that the decrease in AbsBlue absorbance under defined illumination conditions (dAbsBlue) is proportional to the rate of sample degradation and the formation of the LSF aftertaste. AbsBlue absorbance values were measured using the Colorturb device. Each measurement was repeated three times, and the average and standard deviation were calculated for use in subsequent analyses.

2.10 Preparation of samples with a defined level of light degradation

The samples were first removed from refrigeration and allowed to reach room temperature. The initial AbsBlue level of each sample was measured using Colorturb. To ensure accuracy and assess variability in the measurement method, each sample was measured three times, with the final value calculated as the mean of these measurements. The sample was then placed into the illumination adapter, which emits light at a wavelength of 450±30 nm, until the desired change in dAbsBlue was achieved.

During the exposure process, periodic measurements were conducted. Based on our experimental findings, measurements every 5 minutes during the first 20 minutes of exposure and every 10 minutes thereafter proved sufficient. Once the target level of dAbsBlue change was reached, the sample was stored in a light-free environment for 24 hours. The following day, the sample was prepared for evaluation by the sensory panel.

2.11 Triangle Test

The triangle test is a technique for determining whether there is a detectable difference among two products due, for example, to changes in processing, inappropriate storage, etc. The method is a forced-choice procedure, i.e., the assessor must decide even if he/she is not sure about the decision. During the test, each assessor is presented with one different and two alike samples. All three samples are presented at once and tasted from left to right. The six possible order combinations of samples must be randomized across assessors, who should identify the odd sample and record the answer. Details are described in the ISO standard (ISO 4120:2021).

In triangle difference test, the probability p^* of choosing a correct answer by chance is 1/3 and the probability of choosing an incorrect answer by chance is 2/3. If the assessor can distinguish samples, the chance of responding correctly increases. This, from a statistical point of view, leads to a one-sided test about p^*, where we test whether the assessors respond

by chance or not. More precisely, the null hypothesis is the statement that assessors cannot distinguish between the presented samples and respond by chance, i.e. $p^* = 1/3$, and alternative hypothesis is that $p^* > 1/3$. The null hypothesis is rejected if the number of correct responses is "large".

Final decision is made either by comparing the test statistic to a critical value or equivalently by evaluating the corresponding p-value. In practice, the significance level α (α-risk or Type I error) must be fixed first and appropriate critical value C_α, *i. e.* the minimal number of correct responses out of the total number of N assessors required to reject the null hypothesis with the risk α, calculated. Table 1 presents exact critical values C_α calculated using the binomial distribution for α = 0.05 and α = 0.01. Further, recall that the so-called p-value is the maximum probability of obtaining a test result, assuming that the null hypothesis is correct (assessors answer by chance). A small p-value means that such an extreme observed outcome would be very unlikely under the null hypothesis. For more details, see Anděl (1998) or Wasserstein and Lazar (2016). The p-value of a correct answer by chance in the triangle difference test can be calculated using the formula

$$p = 1 - \sum_{j=0}^{k-1} \binom{N}{j} \cdot \left(\frac{1}{3}\right)^j \cdot \left(\frac{2}{3}\right)^{N-j} \quad (3)$$

where N is the number of assessors and k is the number of those who gave the correct answer. The higher the number k of correct answers from the assessors, the smaller the resulting p-value. The p-value is compared to α, and if it is smaller than α, we reject the null hypothesis and conclude that the assessors are able to distinguish between the tested samples.

Table 1 *Critical values for a triangle test*

N	$C_{0.05}$	$C_{0.01}$
4	4	-
5	4	5
6	5	6
7	5	6
8	6	7
9	6	7
10	7	8
11	7	8
12	8	9
13	8	9
14	9	10
15	9	10

2.12 Process of Sensory Tasting

The panel sensory tastings were conducted in sufficiently large and well-ventilated common premises at Charles University between December 2022 and July 2023. Most assessors were recruited through a call organized at the Budeč dormitory, where the tests were held and promoted via its social networks. Consequently, the majority of participants were students and employees residing in the dormitory, ranging from the age of 19 to 26.

To ensure comfort and minimize interference, a minimum two-meter distance was maintained between participants, and windows in the tasting room were kept open for air circulation. Each panel consisted of at least six lay assessors, both men and women, without formal training in beer sensory analysis. Participants were provided with basic information about the experiment's objectives and instructions on identifying LSF. A protocol was also distributed to record their assessments.

The beer samples were initially prepared and stored in a separate room to prevent early exposure to odours and then brought to the participants in the tasting room. Each participant received three glasses of beer: two identical, undamaged samples and one spoiled sample. Following the triangle test procedure, participants were tasked with identifying the odd sample. Samples were presented one at a time, and participants were allowed to sniff and taste them. After all assessments were completed, the collected protocols were analysed.

2.13 Recommended Guidelines for the Organizing Panel Tastings of Photodegraded Beer

Based on the experience gained during our experiments, we recommend adhering to the following guidelines when organizing lay panel tastings of photodegraded beer:

- Provide lay assessors with basic information at the start of the experiment. This should include the objectives of the study, instructions on identifying LSF, key characteristics to focus on, and potential misleading factors.
- Prepare samples in a location separate from the tasting room to avoid premature saturation of the air with LSF.
- Ensure that all samples are at the same temperature and served in opaque containers without beer foam.
- Close bottles immediately after pouring to minimize odour release.
- Be aware that LSF quickly saturates the air. Even in large, well-ventilated rooms, opening a bottle of photodamaged beer can fill the air with LSF almost instantly, which may interfere with the selection of the odd sample. Good ventilation and open windows throughout the tasting process are therefore essential.

- Fatigue among lay assessors was observed after a single tasting session, reducing their ability to distinguish beer accurately. For this reason, multiple tastings in a row with the same panel are not advisable.
- Each 500 mL bottle allows for the preparation of up to nine samples. If more assessors are required, several bottles must be used. In such cases, ensure that the bottles have identical optical properties (e.g., AbsBlue absorbance) so that light degradation occurs at the same rate during illumination.

3 Results and discussion

Our tests focused on optimizing the lay sensory panel and identifying parameters that would ensure reliable and relevant results. Throughout the experiments, numerous sensory tastings were conducted to evaluate and refine the sample preparation process, the experimental procedure, and the preparation of assessors for the tastings.

3.1 Size of the Lay Sensory Panel

When testing for difference, the standard (ISO 4120:2021) recommends using 24–30 assessors, whereas testing for similarity requires to double that number. However, these numbers are practically unattainable for our purposes, as even large multinational corporations rarely have the capacity to routinely employ panels of this size. For our study, we set the significance level to $\alpha=0.05$. According to Table 1, the minimum number of assessors required to reject the null hypothesis at this significance level in a triangle test is four. Nevertheless, we do not recommend such a small number of assessors, as the statistical power of the test becomes insufficient. Furthermore, Lawless and Heymann (2010) notes that in lay panels, up to one-fifth of members may fail to detect differences and resort to guessing. Therefore, we determined that the minimum number of assessors necessary to achieve even a rough decision is six. Generally, larger panels yield more reliable results.

Additionally, we verified that one 0.5 L bottle degraded by light can produce test samples for a maximum of nine assessors. Beyond this, the sample sizes become insufficient for reliable sensory evaluation. As a result, we organized sensory experiments with panels of six to nine assessors. This setup is space-efficient, and the preparation of samples and evaluation of results can be managed by a single individual. An additional advantage is that all assessors evaluate the same set of samples.

3.2 Assessors' fatigue

One of the main challenges in testing for the presence of LSF is assessor fatigue. To investigate this, we conducted repeated tastings with the same panel during a single session. Each tasting round was separated by a 10-minute break, during which the tasting area was thoroughly ventilated. Additionally, assessors were provided with a neutralizing snack consisting of white bread rolls and low-fat cheese.

The session was organized into three rounds. In the first round, all assessors were presented with three samples of non-damaged beer. Following a 10-minute break for ventilation and sensory neutralization, the second round featured two non-damaged samples and one damaged sample exposed to light for 30 minutes. After another 10-minute break, the third round was conducted with the same setup as the second: two non-damaged samples and one light-damaged sample exposed for 30 minutes. The results of these repeated tastings are summarized in Table 2, which measures the degree of damage by the decrease in dAbsBlue, with individual columns presenting the observed values for each round.

Table 2 *The influence of assessors' fatigue*

	round 1	round 2	round 3
illumination time (min)	0 (blind test)	30	30
change of dAbsBlue (a.u.)	0.0000	-0.0812	-0.0796
number of correct answers	–	5	1
number of evaluators	7	7	7
p-value of the test	–	0.0453	0.9415
significance of the test	–	sufficient to reject the null hypothesis on α = 0.05	insufficient to reject the null hypothesis on α = 0.05

The damaged samples used in the second and third rounds were nearly identical, and previous experiments confirmed that the level of damage was sufficient for significant and detectable changes in the beer. While assessors performed well during the second round, their ability to correctly identify the damaged sample declined in the third round. Many assessors reported in their oral

feedback that their decisions in the third round were made at random. Conversely, the ability to make accurate decisions was maintained in the first round, where all samples were undamaged, serving as a blind test. These findings support the hypothesis that olfactory sensors become quickly saturated at higher LSF intensities and require a significant amount of time to recover.

3.3 Determining the degree of Light Degradation detectable by Lay Sensory Panel

The degree of light degradation in beer samples is expressed as dAbsBlue. Smaller dAbsBlue values indicate less pronounced differences between the light-damaged and undamaged samples, making it more challenging for assessors to identify the odd sample. To determine the minimum dAbsBlue difference detectable by lay assessors, we prepared beer samples with varying levels of light damage, corresponding to different dAbsBlue values, and presented them to a sensory panel.

The process began with measuring the initial AbsBlue value of each beer sample prior to light exposure. The samples were then illuminated until the desired decrease in dAbsBlue was achieved, which was confirmed through three repeated measurements. Samples with defined levels of light damage were subsequently presented to the sensory panel following the triangle test protocol. The sensory panel included 15 groups of lay assessors, with a minimum of six participants in each group.

The results of the tastings, summarized in Table 3, revealed a clear relationship between the degree of light damage and the ability of lay assessors to identify the odd sample. At low dAbsBlue levels, correct identifications were close to random guessing, whereas at higher levels of light damage, the accuracy of identification significantly increased.

3.4 Absorbance development curves

Figure 2 illustrates the development curves of absorbance values (dAbsBlue) for the samples during illumination (light degradation) in the illuminator. As anticipated and consistent with previous measurements, see Gabriel et al. (2022b), light degradation intensifies, and AbsBlue decreases with increasing illumination time. The final dAbsBlue changes after 50 minutes and 120 minutes of illumination are highlighted with arrows in Figure 2. From the measured curves, the resulting dAbsBlue values at the end of illumination were determined for all individual samples. The standard deviation of repeated measurements for illuminated samples was ±0.003 AU, while the standard deviation of the resulting dAbsBlue values was ±0.004 AU.

The absorbance development curves for individual samples overlap within the measurement error, indicating that light degradation occurs with the same intensity across all samples. This confirms that the samples selected for light degradation were nearly identical, and at the same illumination time, all samples exhibited uniform levels of degradation.

3.5 Results of Sensory Testing

Table 3 summarizes the results of sensory tests and sample analyses. The illumination time, decrease in absorbance (dAbsBlue), and decrease in RF content (dRF) characterize the extent of light degradation in the sample. The number of evaluators (N) and the number of correct answers (k) are outcomes of the triangle sensory tests. The *p*-values were calculated from the test results (*k* and *N*) using Equation (3). Consistent with our assumptions and previous measurements, see Gabriel et al. (2022b), the decrease in absorbance (dAbsBlue) strongly correlates with the decrease in RF content (dRF), with a high squared correlation coefficient (R^2=0.98).

Figure 3 illustrates the dependence of the *p*-value from the triangle sensory test on the light degradation of the sample, characterized by the decrease in absorbance (dAbsBlue). As shown in Figure 3 and Table 3, the *p*-values of the triangle sensory tests decrease as the exposure time in the illuminator increases. This reflects the practical observation that sensory panels can detect beer

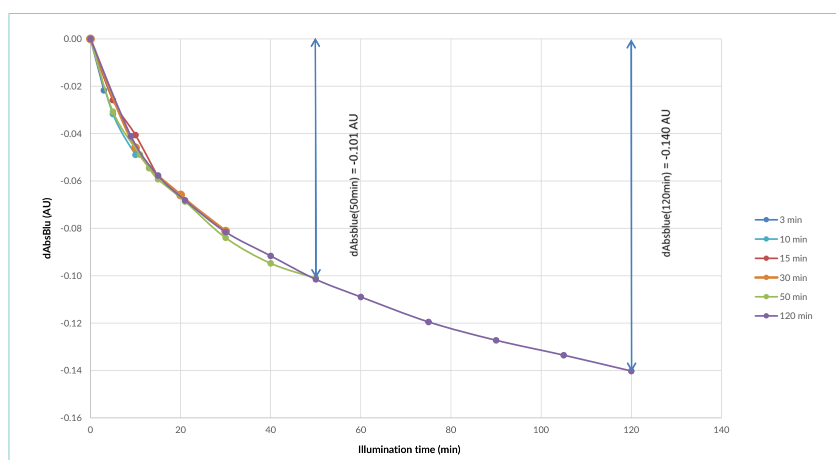

Figure 2 *Development curves showing the absorbance values of the samples (dAbsBlue) during illumination (light-induced degradation) in the illuminator. The final changes in dAbsBlue absorbance after 50 and 120 minutes of illumination are indicated with arrows.*

degradation at higher levels of light exposure (larger absorption changes) but are unable to differentiate between samples when the exposure time is short (smaller absorption changes). This relationship is statistically significant at commonly used significance levels.

Using a 95% confidence level (p-value < 0.05) as the threshold for significant confirmation of the panel's ability to distinguish between light-degraded samples, we can conclude that the panels successfully detected beer degradation when the decrease in absorbance exceeded 0.08 AU.

Our analysis involved fitting an exponential curve to the p-values to model their dependence on the increase in dAbsBlue. The fit achieved an R^2=0.98, indicating an excellent correlation. This result suggests that the ability of lay evaluators to distinguish between damaged and undamaged beer samples improves as the level of damage to the beer increases. Figure 3 illustrates the fitted curve and its intersection with a p-value of 0.05 at an absorbance value of 0.08 AU.

The error bars in Figure 3 represent the change in the p-value if the number of evaluators providing correct answers (k) in the sensory test were to vary by ±1. It is important to note that these intervals are significantly influenced by the relatively small size of the sensory panel.

The change in AbsBlue during the light degradation of beer is dependent on the optical path of the beam through the bottle. When comparing different types of beer, it is necessary to normalize the values to a unit optical path for accurate comparisons.

The primary limitation of our study is the relatively small number of participating assessors, which may reduce the reliability of the statistical results. This limitation arose from challenges in sample preparation and volunteer recruitment. Figure 2 demonstrates that absorbance measurements using the Colorturb device allow for the selection of nearly identical bottles within a batch and the preparation of samples with consistent levels of light degradation. This capability enables sensory tests with a larger number of assessors, which would improve the precision in determining the threshold for assessors' ability to differentiate between damaged and undamaged beer samples.

4 Conclusions

In our study, we employed a lay sensory panel to evaluate the degree of light degradation in beer, as the majority of beer consumers are non-professional assessors. The primary objective was to determine the level of light degradation that lay assessors can reliably distinguish.

We focused on the triangle sensory test with lay assessors and identified parameters necessary to ensure meaningful results. Our findings indicate that a minimum

Table 3 *Results of sample analyses and triangle sensory panel tests with corresponding p-values*

	Panel test 1	Panel test 2	Panel test 3	Panel test 4	Panel test 5	Panel test 6
time of illumination (min)	3	10	18	30	50	120
change of absorption dAbsBlue (AU)	0.022 ± 0.004	0.044 ± 0.004	0.060 ± 0.004	0.081 ± 0.004	0.101 ± 0.004	0.140 ± 0.004
change of RF content dRF (mg/l)	0.028 ± 0.004	0.068 ± 0.010	0.075 ± 0.011	0.117 ± 0.026	0.151 ± 0.022	0.204 ± 0.030
***L* (number of evaluators)**	6	6	6	7	9	7
***k* (number of evaluators giving the correct answer)**	3	4	4	5	6	6
***p*-value**	0.320	0.100	0.100	0.045	0.042	0.007

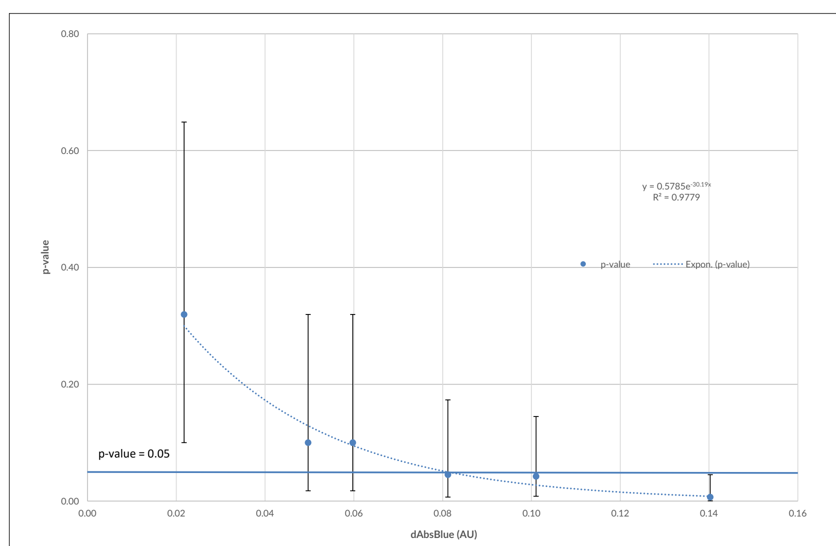

Figure 3 *Dependence of the p-value from the triangle sensory test results on sample degradation caused by light, as characterized by a decrease in dAbsBlue absorbance*

of six assessors is required for at least a rough decision. With a 95% confidence level, we concluded that, for the beer tested, sensory panels were able to detect beer degradation when the decrease in absorbance exceeded 0.08 AU in a bottle with an optical path of 5 cm. By fitting an exponential curve to the *p*-values, we achieved an R^2 value of 0.98, reflecting an excellent fit. This result suggests that the ability of lay assessors to distinguish between damaged and undamaged beer samples improves as the extent of damage increases. While the precision of individual sensory panels of six to nine assessors is limited, our experiments demonstrated that repeated panel evaluations yield statistically significant results. The threshold for distinguishing damaged from undamaged beer could be determined more accurately by conducting more tastings with larger panels.

Since the sensory panel assessed only the differences between samples and not the presence of MBT, it was essencial to ensure that the samples were sensory identical before light degradation. Therefore, determining the homogeneity of key parameters, such as TIPO (Total International Pale Lager Original), within the tested batch is recommended to maintain consistency. When measuring absorbance directly in a bottle, the Colorturb device enables a selection of samples with identical optical properties, preparation of multiple samples with consistent light degradation, and an execution of sensory tests with larger panels. Future research should aim to establish the thresholds for light degradation changes in sample absorbance, and corresponding RF content decreases that lay sensory panels can detect across various beer types and brands. We are currently preparing experiments to replicate this approach with different types of Czech beers, with the primary goal of verifying that changes in sample absorbance and RF content are reliable markers of light degradation in beer.

Regarding practical applications, it would be valuable to compare the development of accelerated light damage with natural light damage under typical household conditions. Such comparisons could enhance our understanding of how light damage occurs in domestic environments and inform about potential methods for its prevention.

5 Acknowledgments

The work of the first author was funded by the MFF UK SFG grant. The work of the second author was enabled by the Ministry of Agriculture of the Czech Republic, institutional support No. MZE-RO1918. The work of the last author was partially subsidized by the GAČR 23-05737S grant. The authors thank Professor P. Sladký for his encouragement and valuable comments.

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