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Multispectral Imaging of Wok-Fried Vegetables

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Abstract. *Quality control in the food industry is often performed by measuring various chemical compounds in the food involved. The authors propose an imaging concept for acquiring high-quality multispectral images to evaluate optical reflection changes in carrots and celeriac over a period of 14 days. For comparison, sensory analysis was performed on the same samples. Prior to multispectral image recording, the vegetables were prefried and frozen at −30 °C for 4 months. During the 14 days of image recording, the vegetables were kept at +5 °C. In this period, surface changes and thereby reflectance properties were very subtle. However, they noted statistically significant differences for some wavelengths and combinations of wavelengths. The corresponding sensory tests showed weak differences over the 14 days (significant at a 10% level of significance), which makes it the more important that the authors were able to detect minor changes using multispectral imaging. From our findings, it seems probable that oxidation caused the changes over time. © 2012 Society for Imaging Science and Technology.*
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INTRODUCTION

The commercial market for convenience food is increasing in both the retail market and food service markets due to trends in demography and lifestyle.[1] Meal elements are robust, semiprepared convenience components, stabilized by cooling, or in some cases by freezing, for a given short period of time and based typically on meat, fish, or vegetables. Meal elements are prepared industrially or at a central kitchen unit, and after preparation the meal elements are distributed to professional satelite kitchens, where the elements can be assembled and reheated without much processing before serving.[2] Widespread use of meal elements requires that they can be produced and distributed in a way that minimizes quality losses. Earlier studies have shown that stir-fried vegetable meal elements have promising properties with respect to high culinary quality and robustness toward freezing and thawing, thereby potentially solving a major hindrance for the use of heat-treated vegetables as meal elements.[3] The stir-fried vegetables can be produced by a new process for continuous stir-frying at industrial scale, which has been introduced for producing convenience high-quality meal components from the raw.[3] A prolonged shelf-life of the meal elements may be achieved by applying the freeze-chill concept in distribution.[4,5]

There is increasing interest in the combined technology of freeze-chilling, which involves freezing and frozen storage, followed by thawing and chilled storage.[6] Freeze-chilling allows the manufacturer flexibility in manufacturering and distribution, i.e., products can be prepared in bulk, frozen, thawed, and released as chilled products on demand. Only little information on the quality and safety of freeze-chilled foods exists, although research has been carried out on fish.[7,8]

Quality control in the food industry is an important issue. Depending on the food product, different parameters are considered important for the overall quality estimation of the food product. Parameters such as surface color, texture, and appearance are very general and should be assessed in most quality estimation scenarios. The color is an important quality parameter for food products as a change in surface color is the first quality parameter that is evaluated by the consumer. Online quality inspection for food process control is today often done by human expert operators, who have many years of experience. The color may also be evaluated by a colorimeter like the Minolta Chroma Meter or Hunterlab, which uses a stable light source to illuminate a small surface of roughly 1 cm^2 and measures the reflection from the surface. However, the trend seems to point toward fast, noninvasive inspection methods such as near-infra red (NIR) technology for quality inspection in different food process control tasks. Brosnan and Sun[9] reviewed vision technology and color cameras in food application. The use of multispectral imaging in the visible as well as in the NIR area of the electromagnetic spectrum can be used to quantify chemical properties of food, and thereby state its level of quality, instead of human operators or standard NIR measurement methods. By employing imaging instead of point measurements, it is possible to gain more spatial information about the process, which makes it possible to assess nonchemical as well as chemical quality features. Nonchemical quality features are evaluations of, e.g., piece-size, shape, and texture. Daugaard et al.[10] used multispectral vision technology

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for quality control in a continuous frying process of meat and are able to assess quality parameters for the meat frying process.

In this study, we are specifically investigating the quality changes of prefried vegetables, as an example of meal elements for professionally prepared meals, with regards to change in surface color and sensory properties after freeze-chilling and during thawing at +5 °C over a period of 14 days. We would like to investigate whether multispectral vision technology can be used to detect quality changes in prefried vegetables during a storage period of 14 days at +5 °C. Celeriac and carrots are the subjects of this study, and we measured the reflectance properties using a multispectral imaging device called VideometerLab, which will be described in the "Materials and Methods section."

The sensory quality of the wok-fried celeriac and carrots is assessed using the Quality Index method (QIM) originally developed for fish.[11] QIM is an objective sensory method based on significant sensory parameters, and it consists of a score system for each parameter with scores from 0 to 2 or 3 demerit points. The scores for all the characteristics are then added to give an overall sensory score; the so-called Quality Index. QIM gives scores of 0 for very fresh products and increasingly larger scores as the product deteriorates. The QIM schemes are originally developed for fish, and QIM schemes for several fish species have been published.[12] These schemes are followed by pictures and detailed descriptions of all parameters. The sensory analysis requires that the samples are reheated before assessment, as otherwise it is not possible to assess taste and smell. This is of minor relevance in this study, as we are interested in the overall changes, measured by imaging before preparing the vegetables, and assessed by consumers after preparation.

MATERIALS AND METHODS

Experimental Design

In a pilot plant, the raw products (celeriac and carrots cut into cubes of size approximately 0.5 cm^3) were prefried using a special frying machine; "the continuous wok."[3] After frying, the products were packed in polyethylene bags in 500 g portions and frozen to −30 °C. After 4 months of freezing, the bags with the prefried vegetables were removed from the freezer and thawed up to 14 days at +5 °C in a refrigerator. The bags were permeable for oxygen and an alternative could be packing using a controlled atmosphere without oxygen, but this could lead to other problems such as development of anaerobic bacteria.

On each day of analysis (days 2, 4, 8, 10, 12, and 14), one polyethylene bag was taken out of the refrigerator, and the vegetables were analyzed using sensory analysis and VideometerLab.

Sensory Analysis

An internal panel consisting of 3–4 assessors performed the evaluation. They were all selected and tested according to international standards[13] for their ability to make sensory evaluations, i.e., describe and quantify appearance, odor, flavor, and texture characteristics and were especially trained in the principles of QIM evaluations.[14] Training was conducted over two training sessions prior to the first trial.

For each type of vegetable, an individual QIM scheme was developed in analogy to how QIM schemes have been developed for several fish species.[14] The scheme was developed during pilot sessions using prefried celeriac and carrots with different storage days. In Appendices A and B, the QIM schemes for celeriac and carrots can be seen. At the sensory assessment, appearance, smell, taste, and texture were assessed.

Before each assessment, 40 g of each sample for each assessor was placed in an aluminum tray and reheated at 200 °C for 10 min in a convection oven. At the same time, porcelain trays and lids were heated. After heating, the samples were portioned in the warm porcelain trays and lids were put on. The trays were marked with a three-digit code in randomized order. The evaluations were performed in separated booths under normal daylight and at ambient temperature.

The Quality Index of the sensory data was calculated as the total sum of demerit points given to each vegetable and averaged over all assessments made on the vegetable with equal storage conditions.

Furthermore, a two-way univariate analysis of variance (ANOVA) was used to estimate the effects from days and assessors on the basis of the mixed effects model

$$S_{ijr} = \mu + a_i + D_j + aD_{ij} + \varepsilon_{ijr}, \tag{1}$$

where S_{ijr} is the score for the ith assessor, on the jth day and for the rth replicate, and a_i is the assessor effect, μ is the overall mean, D_j is the day's effect, aD_{ij} is the interaction, and ε_{ijr} is the random replicate error; as described in Ref. 15. The assessor effect was modeled as a random effect, and the interactions were, therefore, also assumed random, whereas the day's effect was assumed fixed. We tested the null hypothesis that there was no effect from days, H_0: $D_1 = \ldots = D_J = 0$, and the null hypothesis that there was no effect from the interactions, H_0: $aD_{ij} = 0$, $i = 1,\ldots I$, $j = 1,\ldots,J$. The models were fitted and the effects tested under optimization of the log-likelihood criterion with a χ^2-test.

Multispectral Imaging

On each day of analysis (days 2, 4, 8, 10, 12, and 14), one polyethylene bag was taken out of the refrigerator, and the vegetables were digitized using VideometerLab.[16] VideometerLab acquires multispectral images in up to 20 different wavelengths ranging from 430 to 970 nm. The vegetables are placed inside an integrating sphere which has its interior coated to obtain high diffuse reflectivity for optimal light conditions. In the top of the sphere, a camera is located with the sensitivity spectrum. The sensitivity decays toward the near-infra red area, which means that the

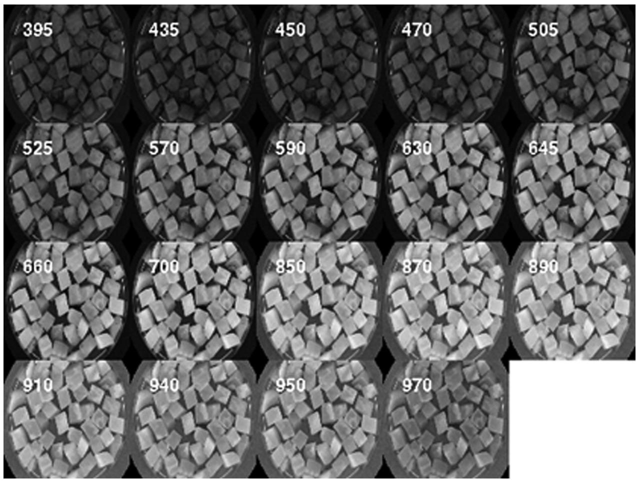

Figure 1. Plot showing all spectral channels of a celeriac sample.

illuminating diodes in this area need more power to achieve the same level of intensity as the visible bands. The light-emitting diodes (LEDs), with the spectral radiant power distributions, strobe successively, resulting in an image for each LED of dimensionality 1280×960. These are calibrated radiometrically as well as geometrically to obtain the optimal dynamic range for each LED, as well as to minimize distortions in the lens and thereby achieve pixel-correspondence across the spectral bands. The well defined and diffuse illumination of the optically closed scene aims to avoid shadows and specular reflections. Furthermore, the system has been developed to guarantee the reproducibility of the images collected. This allows for comparative studies of images taken at different times.[17]

In previous work,[18] images as seen in Figure 1 were acquired using VideometerLab. The spectral images were segmented in two steps with an automated process: step one consisted of isolating the total vegetable area in the image and was performed using labeling from Otsu's method,[19] and subsequently performing a canonical discriminant analysis[20] to assign the class of interest (carrot/celeriac) to the labels. Step two consisted of separating the pieces from each other, and to do this we used a Watershed segmentation,[21] which makes use of spatial and gradient information to separate the vegetable pieces. Each piece of vegetable consisted of approximately 15,000 to 20,000 pixels. In previous work, a feature vector was extracted for each vegetable piece, consisting of a number of percentiles in the probability distribution functions based on ratios of pixel intensities in different wavelengths. Here, we examine reflection changes in pure wavelengths. We consider t-tests to evaluate the significance of reflection changes between days.

RESULTS AND DISCUSSION

Sensory Analysis

The Quality Index results are shown in Table I. The total sum of the assessor scores is rather low for both carrots and celeriac, even after 14 days of storage at +5 °C. For the ANOVA analysis of the scores of each question, the effect of day on the discoloration of celeriac had a p-value of 0.088. In comparison, the p-value of the effect of day on discoloration of carrots was 0.46. The discoloration scores are illustrated as a function of the days in Figure 2.

Only one other effect was significant at a 10% level of significance, namely, the interaction effect of assessor and day for the off-taste scores of celeriac. The p-value of the test was 0.074. It is, thus, possible that the discoloration noted occurs simultaneously with a slightly noticeable off-taste.

Table I. Quality Index calculated as the total sum of demerit points given to each sample of vegetables and averaged over all assessments on equal storage days; the standard deviation of the sums is given in parentheses.

Days	Carrots	Celeriac
2	2.75 (1.39)	2.38 (1.6)
4	2 (0.63)	2.46 (1.61)
8	1.88 (1.73)	3.75 (1.75)
10	2.5 (1.76)	2.33 (0.98)
12	3.63 (1.85)	3 (2)
14	2.75 (2.18)	4.83 (1.6)

Multispectral Imaging

In order to assess changes in reflection on a day-to-day basis, unpaired t-tests were carried out on features extracted from each vegetable piece. Features calculated as the 5th, 10th, 25th, 50th, 75th, 90th, and 95th percentiles of pixel intensity values within each vegetable piece were inspected for trends of change in reflection as a function of days kept in the refrigerator. Representative results from the 5th percentile feature are shown in Figure 3 for carrots and Figure 4 for celeriac.

A total of 358 carrot samples and 389 celeriac samples distributed over six different sample days were tested for group-wise differences. Only successive days were compared, as indicated on the y-axis in Figs. 3 and 4. These figures show p-values for the t-test with null hypothesis, that there is no difference in mean values between days. A gray background represents days having significant differences at a 5% level. The statistical tests show that for carrots, we are able to verify a significant change in the mean from days 2 to 4 for all wavelengths up to 890 nm. This pattern was similar for other percentiles than the illustrated 5th percentile. For carrots, after day 4 we note only a few significant changes in mean of the visible wavelengths and from days 12 to 14 in the NIR wavelengths. However, for celeriac, we are able to significantly track a change every 4–6 days. However, the changes are not as clear as those reported in Ref. 16, since these statistics are based on pure wavelengths rather than ratios of wavelengths. As for carrots, the most significant change is found from days 2 to 4.

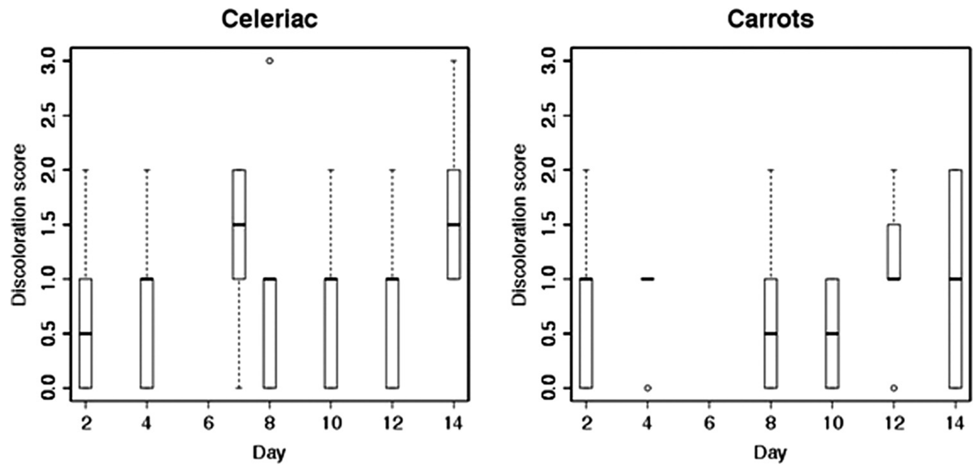

Figure 2. Boxplots of discoloration scores as a function of days for celeriac and carrots, respectively.

Day	395	435	450	470	505	525	570	590	630	645	660	700	850	870	890	910	940	950	970
[2,4]	0.01	0.01	0.01	0.01	0.01	0.02	0.04	0.01	0.00	0.00	0.00	0.00	0.01	0.02	0.05	0.22	0.24	0.24	0.86
[4,8]	0.81	0.85	0.89	0.85	0.82	0.83	0.89	0.95	0.95	0.91	0.93	0.82	0.88	0.79	0.84	0.80	0.78	0.77	0.97
[8,10]	0.74	0.87	0.82	0.83	0.76	0.61	0.27	0.31	0.45	0.49	0.58	0.78	0.92	0.87	0.93	0.97	0.97	0.97	0.82
[10,12]	0.16	0.31	0.29	0.30	0.25	0.13	0.01	0.02	0.07	0.10	0.16	0.36	0.64	0.61	0.46	0.24	0.23	0.23	0.06
[12,14]	0.30	0.34	0.29	0.28	0.21	0.17	0.15	0.22	0.35	0.32	0.32	0.31	0.15	0.13	0.07	0.03	0.03	0.03	0.01

Wavelength (nm)

Figure 3. Unpaired two-sample t-tests for difference in 5% percentile reflection values between all days for the carrot dataset. Shown values are *p*-values found in the t-tests and grayed-out fields indicate significant differences between days indicated at the y-axis at a 5% level.

Day	395	435	450	470	505	525	570	590	630	645	660	700	850	870	890	910	940	950	970
[2,4]	0.01	0.01	0.01	0.01	0.01	0.01	0.05	0.04	0.03	0.04	0.05	0.08	0.66	0.82	0.79	0.44	0.52	0.51	0.22
[4,8]	0.05	0.06	0.08	0.11	0.17	0.20	0.41	0.46	0.49	0.54	0.59	0.71	0.47	0.43	0.44	0.31	0.25	0.25	0.15
[8,10]	0.06	0.03	0.03	0.02	0.01	0.00	0.01	0.01	0.01	0.02	0.02	0.05	0.16	0.20	0.26	0.35	0.34	0.34	0.46
[10,12]	0.63	0.77	0.76	0.69	0.59	0.53	0.42	0.47	0.63	0.65	0.72	0.91	0.70	0.66	0.72	0.82	0.81	0.81	1.00
[12,14]	0.09	0.10	0.08	0.07	0.06	0.05	0.02	0.03	0.04	0.04	0.05	0.07	0.32	0.44	0.50	0.71	0.81	0.83	0.92

Wavelength (nm)

Figure 4. Unpaired two-sample t-tests for difference in 5% percentile reflection values between all days for the celeriac dataset. Shown values are *p*-values found in the t-tests and grayed-out fields indicate significant differences between days indicated at the y-axis at a 5% level.

Polyethylene bags are permeable for oxygen molecules, which is why we believe the change in the spectra is caused by oxidation of the vegetables. Oxidation causes browning/graying of celeriac and carrots to become more pale and likewise brown. An increasing brown/gray color is a change in a wide range of the spectrum and is essentially a change in brightness. There are significant color changes from days 2 to 4 throughout the visual spectrum for carrots and in a large part of the visual spectrum for celeriac. This coincides with a general shift in brightness for all or a large part of the visual spectra.

CONCLUSIONS

An objective measure of the quality change of carrots and celeriac was proposed, which uses multispectral image analysis. Six images were recorded over 14 days, for two different data sets. Each carrot or celeriac piece was isolated using image analysis, for a total of around 400 pieces, for both carrots and celeriac pieces, respectively. For each wavelength and each piece of vegetable, we conducted a t-test to check for significant differences on a 5% level in a number of percentiles of the light reflectance. We noted significant changes from days 2 to 4 in the reflectance spectrum for both carrots and celeriac, and for the celeriac we noted significant changes continuing until day 14. The corresponding sensory tests showed no difference at a 5% level of significance over the 14 days, and only a difference on the discoloration of the celeriac at a 10% level of significance, which makes it the more important that we were able to detect minor changes using multispectral imaging and could conclude that multispectral vision technology was sensitive enough to detect small quality changes in wok-fried vegetables, while in the sensory analysis the detection limit for sensory changes (using a trained panel) was 14 days.

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APPENDIX A SENSORY ASSESSMENT FORM FOR CARROTS

Sensory assessment form regarding heated wok-fried carrot cubes

Name: __________________ Date: ________ Code: ________

Parameter	Description	Point
Appearance		
Discoloratio	No discoloration, the product is carrot colored as well as it has brownish frying color	0
	Few cubes (less than. 10%) are discolored with brownish tone	1
	Over 10% are brown, colored and crinkled	2
Smell		
Smell of carrot	Distinct smell of carrot	0
	Some smell of carrot	1
	Weak smell of carrot	2
Cloying sweet smell (not fresh carrot-like)	No/none	0
	Yes/present	1
Taste		
Taste of carrot	Distinct taste of carrot, sweet	0
	Some taste of carrot	1
	Weak taste of carrot	2
Frying aroma	Weak frying aroma (light frying aroma)	0
	Some frying aroma	1
	Heavy frying aroma (burnt)	2
Off taste	No off taste	0
	Off taste present	1
Texture		
Firmness (Determined at first bite in the mouth)	Very firm with bite but not like a raw Vegetable	0
	Firm kernel, softer exterior	1
	Soft, and no difference in texture between, kernel and shell	2
	The whole square is soft, tough and spongy	3
Crispyness (crunchyness)	There is a crunchy sound when the sample is being chewed, the sample has a softer shell and a kernel with 'bite'	0
	The sample has a soft shell and a firm kernel, but there is no 'crunchy' sensation	1

APPENDIX B SENSORY ASSESSMENT FORM OF CELERIAC

Sensory assessment form regarding heated wok-fried celeriac

Name: __________________ Date: ________ Code: ________

Parameter	Description	Point
Appearance		
Discoloration	No discoloration, the product has a yellowish color and brownish frying color	0
	Few cubes (less than 10%) are discolored (grey/whitish for celeriac)	1
	More squares (over 10%) are discolored/grayish	2
	All squares are completely grayish	3
Smell		
Smell of celeriac	Distinct smell of celeriac	0
	Some smell of celeriac	1
	Weak smell of celeriac	2
Frying aroma	Weak smell of fried/toasted	0

Parameter	Description	Point
	Burnt smell	1
	Intense burnt smell (grill-like)	2
Taste		
Taste of celeriac	Distinct taste of celeriac	0
	Some taste of celeriac	1
	Weak taste of celeriac	2
Sweet taste	Yes/present	0
	No/None	1
Off taste	There is no off taste, the product tastes of fried celeriac	0
	Off taste is present	1
Texture		
Firmness (Determined at first bite in the mouth)	Very firm with bite but not like a raw vegetables	0
	Firm kernel, softer exterior	1
	Soft, and no difference in texture between, kernel and shell	2
	The whole square is soft, spongy, rubber-like	3
Crispyness (crunchyness)	There is a crunchy sound when the sample is being chewed, the sample has a softer shell and a kernel with 'bite'	0
	The sample has a soft shell and a firm kernel, but there is no 'crunchy' sensation	1

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