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LASER LIGHT BACKSCATTERING FOR MONITORING CHANGES IN MOISTURE CONTENT DURING DRYING OF APPLES

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ABSTRACT Measuring and controlling the moisture content of a product during processing is essential in the food industry. The present investigation proposes the use of laser diode sensors at 635 and 785 nm wavelengths as a novel approach for monitoring changes in moisture of apple slices *(Malus domestica)* during drying. We hypothesized that changes in backscattering profiles during drying would allow prediction of changes in moisture content via the mechanism of altered light propagation in the fruit tissue. To test this hypothesis, apple slices were dried in a high precision through-flow laboratory dryer at air temperatures of 60 and 70 °C, with 10 g/kg absolute humidity and air velocity of 0.9 m/s. The moisture content was determined by the standard oven method. Backscattering images of ten slices were acquired every 30 minutes over three hours of drying, with a digital CCD camera connected to a PC. Laser parameters (backscattering area and luminescence) were highly correlated with the moisture content with Pearson coefficients of 0.95 and 0.96, at 635 nm wavelength and of 0.74 and 0.87 at 785 nm wavelength. A multi-factor ANOVA test showed a significant effect of moisture content on the entire scattering profile. In conclusion, light propagation inside the tissue may represent an innovative and reliable technique for rapid and contactless evaluation of apple drying.

Keywords: Apple drying, Moisture content, Laser parameters, Light propagation.

INTRODUCTION Monitoring changes in moisture content during food processing is of pivotal relevance for food industry. Apple is a highly regarded product, which can be consumed fresh or dried. A widely used method for apple drying involves convective hot air. With this technique, the properties of the drying air determine the final moisture content (Lewicki and Jakubczyk, 2004) and varying drying conditions are used on the basis of the use of the final product (Bai et. all, 2002). Online control of the drying process can be achieved by non-destructive optical methods, such as near infrared spectroscopy (McGlone and Kawano, 1998) and computer image analysis (Fernandez et al, 2005). A recent study from our laboratory has provided a new approach to estimate variation in moisture content during drying by means of laser light propagation (Romano et al, 2008). Other studies have shown the feasibility of laser light backscattering to investigate, in a non-invasive setting, the quality of fruits. Light absorption is able to monitor chemical and physical characteristics of fruits such as water content, pigments and texture (Williams and Norris, 2001; Lu, 2004). (Qing et al., 2007;2008) performed parallel measurements of the soluble solid content and firmness of apple during ripening with laser diode at five wavelengths between 680 and 980 nm. A correlation between laser images and quality parameters was obtained using partial least square regression. Monte Carlo simulation was also carried out to examine the optical properties of fruit by measurements of light absorption and scattering coefficient, as these parameters are related to product chemical and physical attributes. Using this method, Baranyai and Zude, (2008) obtained valuable information regarding the damage of the apple tissue. The main goal of this research was to monitor moisture content changes during apple drying by employing laser diode sensors at 635 and 785 nm wavelengths to corroborate the hypothesis that changes in backscattering profiles during drying would allow monitoring of changes in moisture content.

MATERIALS AND METHODS

Material Apple fruits (*Malus domestica*, cv. 'Gala'), grown in Germany, were purchased from a local market in Stuttgart, Germany. The apples were cut into 5 mm thick slices with an electrical vegetable slicer. Only slices free of visible defects were selected for the study.

Laser image laboratory The measurement set up consisted of the optical system, a digital CCD camera and a computer as described below. The optical system included two laser diode modules emitting (i) in the visible light range at 635 nm wavelength with 0.85 mW power and (ii) in the near infrared spectrum at 785 nm wavelength with 12 mW power. The size of the laser beam was 2 x 2 mm and 1.8 x 1.8 mm at 635 nm and 785 nm, respectively. A digital CCD camera (PAX P1-CMO, Optoprim, Germany) was used to collect images of 1280x1024 pixels. Images were analyzed using Adobe Photoshop CS3 by counting pixel of the selected images. The distance between the sample and the camera objective lens was set at 220 mm.

Experimental set up The samples were loaded on a perforated tray and placed in a through-flow laboratory dryer at the institute of Agricultural Engineering in the Tropics and Subtropics, University of Hohenheim. The drying experiments were carried out at air temperatures of 60 and 70° C, with 10 g/kg absolute humidity and constant air velocity of 0.9 m/s. Before each drying experiment, backscattering images from 10 fresh apple slices were acquired. Image acquisition was continued with 10 slices per interval (30 minutes) over three hours of drying. In total, 60 slices were dried for each temperature. The experiment was repeated twice. On each slice, two measuring points, free from visible defects were selected. The surrounding area of the surface close to the incident point was illuminated as a result of photon migration in the fruit tissue. Grey values, corresponding to the light luminescence, ranging from 0 (dark) to 255 (white), were acquired. Furthermore, full scattering width as the sum of the diameter of the incidence area and the surrounding scattering zone was also determined.

When image acquisition was complete, the moisture content wet basis (% w. b.) of each slice was determined by the standard oven method until constant weight was reached (103±2 °C). Multi-factor ANOVA test and Pearson coefficient were evaluated in R statistical software to show respectively the significant effect of moisture content on the entire scattering profile and the relationship between predicted values of moisture content and reference values.

RESULTS AND DISCUSSION

Light propagation in apple tissue Laser images at two different wavelengths acquired at different intervals during drying are shown in Figures 1 and 2. Each image corresponds to a certain level of moisture content of the apple. The values ranged from 86 %, which corresponds to the fresh sample, to 11 % which corresponds to the dried sample, after three hours of drying. The illuminated part represents the backscattering area after light injection. The white point represents the area of maximum intensity of laser light injection, whereas the red area depicts scattered photons.

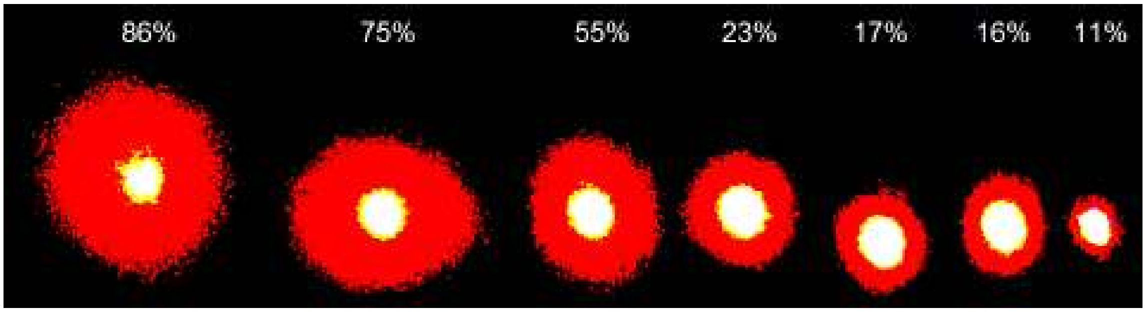

Figure 1. Laser scattering images at 635 nm wavelength at different levels of moisture content (% w.b.)

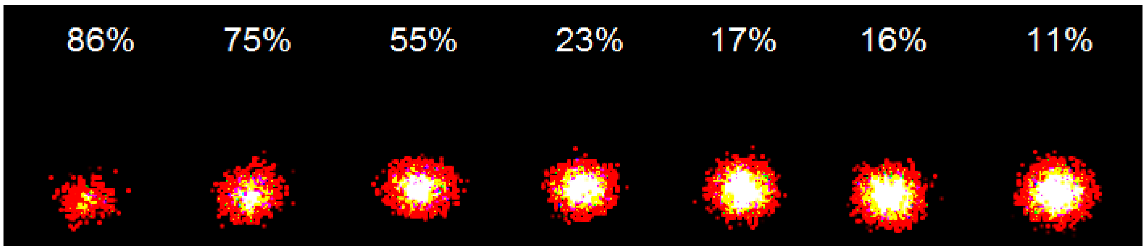

Figure 2. Laser scattering images at 785 nm wavelength at different levels of moisture content (% w.b.)

Visually, it is possible to distinguish two steep decrements in the backscattering area at 635 nm, which might be related to two key falling rate intervals. One falling rate interval can be noticed at moisture content between 75 % and 55 % and another between 55 % and 23 %. It is also worth mentioning that the images of samples with moisture content between 17 % and 16 % display a similar backscattering area. At moisture content of 11% the area is almost diminishing. These results can be explained considering that in pure water, light will have the highest penetration (Qin and Lu, 2009) therefore water loss by evaporation during drying will reduce light propagation in the fruit tissue giving lower photon migration. On the other hand, at 785 nm wavelength (Figure 2), the light signal showed less scattered values compared to 670 nm, with an opposite behaviour: with an decrease of moisture in the backscattering area increased. This may be due to absorption of 785 nm wavelength light by water.

Prediction of the moisture content with laser light at 635 nm and 785 nm A highly positive linear correlation (R=0.95) was found between the backscattering area, analyzed by laser light set at 635 nm wavelength and the moisture content values. On the contrary, an inverse correlation (R=0.74) was observed at 785 nm wavelength (Figures 3 and 4).

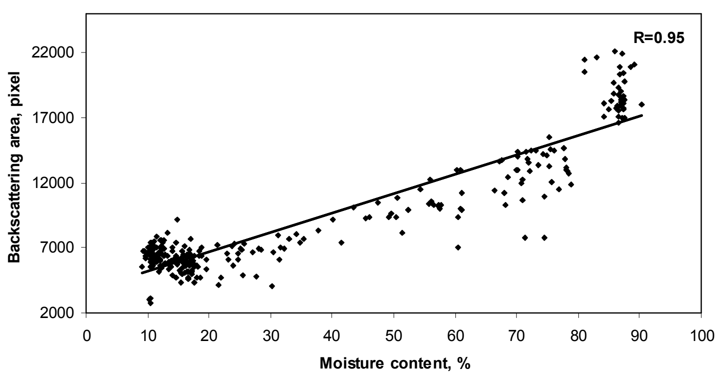

Figure 3: Correlation between backscattering area and moisture content at 635 nm during drying at air temperatures of 60 and 70°C.

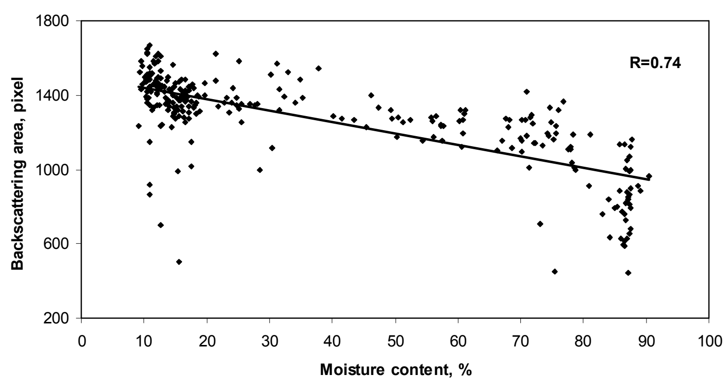

Figure 4: Correlation between backscattering area and moisture content at 785 nm during drying at air temperatures of 60 and 70°C.

The reduction in the backscattering area at lower moisture content (Figure 3), might be determined by reduced light propagation in the fruit tissue. As the slices loose moisture, light penetration decreases due to reduction of inter-cellular spaces. Also, removal of water can determine closer packing of the tissue components, making the tissue structure more opague. This results in reduced scattering, because of the interference effect (Tuchin, 2005) and diminished thickness. As the cell wall becomes more compact during drying, light dissemination into the fruit tissue and further reducing light reflectance is restricted. On the other side, to explain results in Figure 4, we may speculate that in the fruit tissue, with the reduction of moisture, air can replace water in some inter-cellular spaces, giving an increase in near infrared light refraction and thus a higher scattering coefficient, since the difference in refractive index between air and fruit tissue is considerably greater than that between fruit tissue and water. However, it is difficult to expect a clear tendency due to differences in refractive index and light scattering (Qing et al, 2007). Also highly significant statistical correlations between the light luminescence at 635 nm 785 nm and moisture content was found with R=-0.96 and -0.87, respectively (Figures 5 and 6).

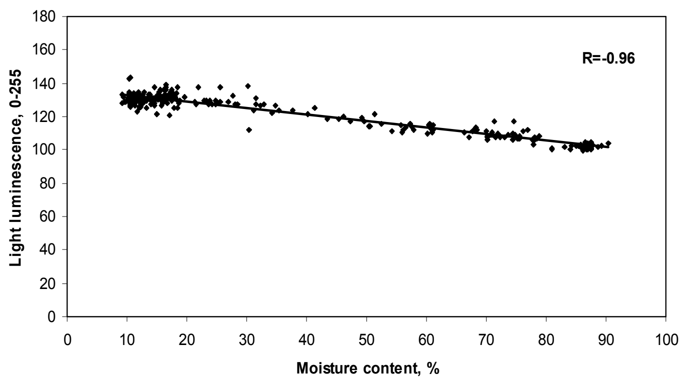

Figure 5: Correlation between light luminescence by gray values and moisture content at 635 nm during drying at air temperatures of 60 and 70°C.

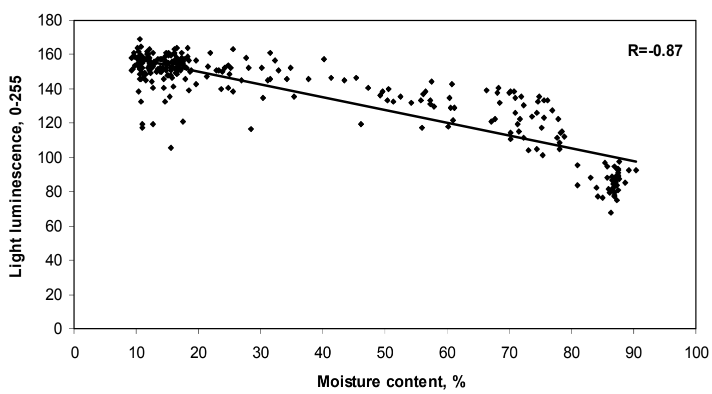

Figure 6: Correlation between light luminescence by gray values and moisture content at 785 nm during drying at air temperatures of 60 and 70°C.

Thus, measurements of light luminescence at 635 nm and 785 nm give a quite accurate estimate of the moisture content. Maximal luminescence at 635 nm was approximately 130-140 at 10-20 % of moisture content, whereas at 785 nm maximal luminescence was around 160 at 10-20% of moisture content. An explanation for these results can be that a decrease in moisture content causes a reduction in visible photon scattering, and, as a consequence, an increase in inner luminescence, due to enhanced light absorption from the apple surface. Statistical analysis (Table 1) unveiled a significant impact ($p<0.001$) of the moisture content on the backscattering area and on luminescence. A significant influence of the moisture content was also observed on the interaction between drying times and laser parameters.

Table 1: Analysis of variance of the effect of moisture content on scattering area (pixel) and gray values (0-255) parameters

Factor	Df	Sum Sq	F values	Pr (>F)
Scattering area	1	203879	6929.543	< 2.2e-16 ***
Gray values	1	15116	513.759	< 2.2e-16 ***
Scattering area: Dying time	1	780	26.524	<5.002e-07 ***
Gray values: Drying time	1	3736	126.983	< 2.2e-16 ***
Residuals	272	8003		

***Significant influence at $p<0.001$

The box-plots of Figure 7 showed decreasing of moisture content of apple fruit as the drying time proceeded. Similar trend was found between scattering width on the slice samples at 635 nm and drying time up to 90 minutes (Figure 8). Toward the end of drying (between 90 min and 180 min), moisture content values as well as scattering diameter showed modest changes. An opposite behaviour of the relationship between scattering width and drying time was observed at 785 nm (Figure 9). A higher standard variation of moisture content values was found after 60 minute drying, which corresponded to higher standard variation in scattering width (100-120 pixels at 635 nm and 43-47 pixels at 785 nm, respectively).

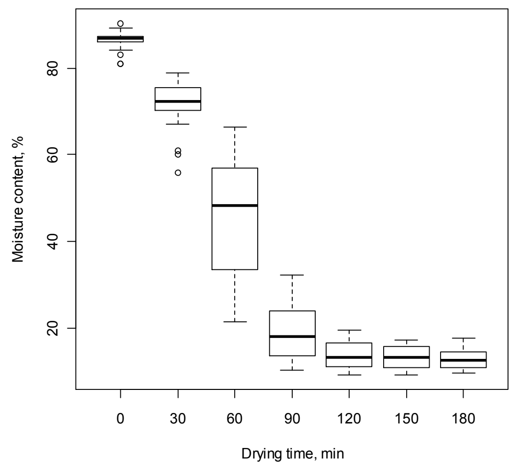

Figure 7: Moisture content vs. drying time for apple fruit.

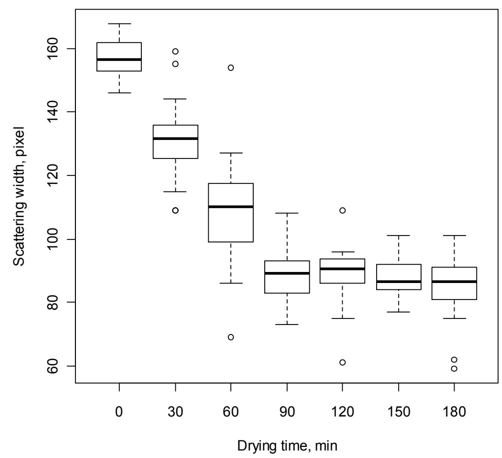

Figure 8: Scattering diameter at 635 nm vs. drying time.

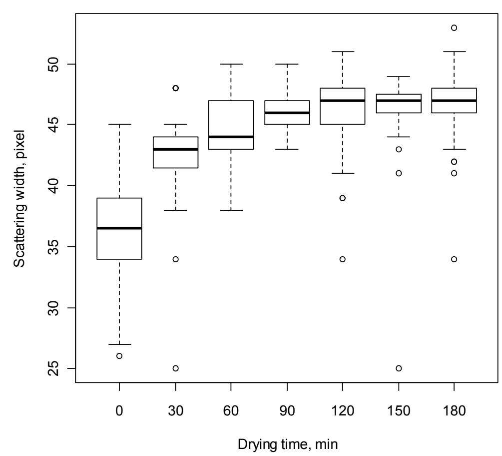

Figure 9: Scattering diameter at 785 nm vs. drying time

CONCLUSIONS Results indicate that laser light measurements in the visible and in the near infrared wavelength range can predict changes in moisture content during drying. Backscattering area, gray values and scattering width were influenced by change of moisture content of apple slices. This technology can represent an innovative and reliable method for rapid and non-invasive monitoring of apple drying. By further investigation and development on-line application of laser light of optimized wavelengths could give continuous information about moisture content and further quality parameters during the drying processes. The next goal of this research will be to increase the variety of fruits and the wavelengths and to identify tissue discoloration during drying by analyzing browning on samples surface in the near infrared spectrum. Additionally, it would be of relevant interest, to examine thermal damage effect due to pigments losses which should result in increase of reflectance, thus high scatter of the photons as a consequence of less absorption at wavelengths in the visible range (green light).

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