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Monitoring quality change of fruit during drying by application of laser light in the red spectrum

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Abstract: The main task of this research is to apply laser backscattering technology to simultaneously predict variations in moisture content and hardness of apples during drying. The backscattering area in pixel numbers, representing the illuminated area after laser light injection, and light luminescence measured by grey values were used for estimating changes in internal quality parameters during drying. Laser light measurement at 635 nm was found to be adequate for predicting changes in moisture content and SSC of apple during drying over different stages. On the contrary, photon scattering at 635 nm is not recommended as estimator of change in hardness during apple drying, based on the results.

Keywords: Malus domestica, photon migration, non-destructive measurements, laser backscattering, moisture content.

1. INTRODUCTION

During drying, quality parameters such as soluble solids content (SSC), hardness, shrinkage or water content as well as microstructure of fruit tissue change according to the applied drying method and conditions (Aguilera 2003; Lewickiy and Jacubczyk, 2004). Standard laboratory techniques, such as the gravimetric method for moisture content determination, the MT test to assess fruit flesh resistance against rupture and refractometer for evaluation of SSC, do not allow a continuous sample control during processing because they are destructive, costly and introduce contamination. Currently, non-destructive and non-contaminating optical methods are used for monitoring and controlling physicochemical quality changes of horticultural products during different harvest and post-harvest processes. Various studies have focused on the potential of light scattering properties to predict food quality, mainly in fresh produce. However, research in this area is still at a preliminary stage. It is known that when a light source touches the fruit, part of the light is reflected, some is transmitted through the product and the other part is absorbed into the fruit tissue. In 1978 Birth reported that only 4% of the light is reflected from the surface and is scattered back through the initial interface. This phenomenon was termed diffuse reflection or light scattering. Multiple scattering occurs in dense scattering media such as fruit. The scattering profile at fruit surface is influenced by the absorption and scattering properties of the fruit. Absorption gives information on chemical constituents while scattering is related to the cell structure (Qin and Lu, 2009). During drying, because of moisture loss, tissues become denser due to decreased volume and higher concentration of cells, organelles and cell walls over the same path length (Vanoli ***et. al.*** 2005). The scattered laser image has the highest intensity at the center and diverges along a radial axis. Therefore, light scattering could be suitable for estimating changes in fruit mechanical and textural properties (Lu and Peng, 2006). Qing ***et al.*** (2008) performed parallel measurements of apple SSC and firmness during ripening using laser diode at five wavelengths between 680 and 980 nm. Previous research (Romano ***et al.*** 2008) established that moisture content and light migration at 670 nm in banana slices during drying, measured by the laser area of the luminescence profile, could be closely correlated. However, additional studies are required to assess the suitability of the laser light propagation into fruit tissues for monitoring in a non-destructive manner internal quality properties during post-harvest treatments such as drying. The main task of this research is to apply laser backscattering technology to simultaneously predict variations in hardness and moisture content on light propagation during apple drying.

2. MATERIALS AND METHODS

Drying experiments

Apple fruits (Malus domestica, cv. 'Gala') grown in Germany were purchased from the local market in Stuttgart, Germany. Slices of 5 mm thickness were obtained by cutting apples perpendicular to the stalk-blossom axis with an electrical vegetable slicer. The samples were subjected to convective hot air drying using a high accuracy through-flow laboratory dryer. Drying experiments were carried out at air temperatures of 50, 60 and 70 °C, at an air velocity of 0.9 m/s and an absolute air humidity of 10 g/kg. Ten slices were sampled from the dryer every 30 min over 3 h and used for further analysis. Sixty slices were dried for each drying condition and three repetitions were performed.

Laser image acquisition

The optical system included a laser diode operating in the visible wavelength range at 635 nm with 0.85 mW power (LDM115P, Imatronic, Herts, UK) and beam size of 2.0x2.0 mm. A digital CCD camera (PAX Cam P1-CMO, Villa Park IL, USA) which gives information of red, green and blue color values was used to obtain images with a resolution of 1280x1024 pixels. To capture images and interpret the color data coming from the camera, the Pax-it software (MIS, Villa Park IL, USA) was used. The surrounding area of the surface close to the incident laser point was illuminated as a result of photon migration in the fruit tissue. Images were analyzed using Adobe Photoshop CS3 by selecting illuminated area for each image and retrieving software calculations. For each image, backscattering area and light luminescence were calculated.

Analysis of moisture content and hardness

Apple slices were evaluated for hardness and moisture Hardness was defined as the maximum force (N) required for puncturing an apple slice. The test was carried out at room temperature (25°C) using a electromechanical analyzer (Instron Universal Testing machine, Model 3365, Norwood, USA) equipped with a 5 mm needle probe and a 5 kN load cell, operated at a crosshead speed of 100 mm/min. Slices were measured in the same location where the laser light was applied. Moisture content (MC) was obtained by the static gravimetric method using a laboratory convection oven (Memmert 500, Schwabach, Germany) at 105 °C until constant weight was reached. Values are given in percent wet basis (%w.b.).

Statistical analyses

Calibration and validation steps were done using R statistical software. Coefficients of determination for evaluating correlations between scattering parameters and reference values were calculated. Prediction models for the best fitting laser parameters were developed and validated with the leave one-out cross validation method. Standard error of cross validation (SECV) was calculated in order to evaluate the prediction capability of each model

3. RESULTS AND DISCUSSION

Laser light distribution in apple tissue

In Figure 1, each image corresponds to a certain stage of moisture content of the apple slices during drying at 60 °C.

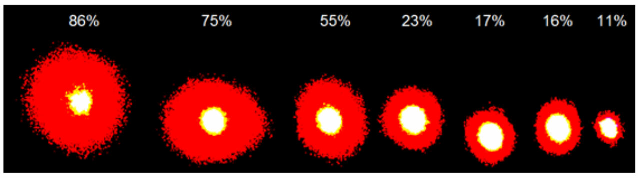

Fig. 1. Laser scattering images at 635 nm wavelength at different levels of moisture content (MC, % w.b.).

The illuminated part (white) represents the direct reflected light, which increases as the moisture decreases as indicated by luminescence. This can be explained by the fact that since water is just a transparent medium in between solids, with less water the distance between solids reduces and photons take a straight trajectory, thus only direct reflection occurs. On the other hand, light penetration becomes more difficult, resulting in reduction of diffuse reflectance. The red area depicts scattered photons, circular to the area of maximum intensity of the incident point. Values ranged from 86 %, which corresponds to the fresh sample, to 11 %, which corresponds to the dried sample after three hours drying. Here it is clear that the scattering around the incident point decreased as the drying time proceeded. Toward the end of drying, values for moisture content as well as for illuminated scattering areas showed only slight changes. Visually, it was possible to distinguish two major 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%. Images of samples with moisture content between 16-17 % displayed similar backscattering areas as did images at a moisture content of 11 %, when the scattering area is almost suppressed. Figure 2 shows the plot profile obtained from the scattering images.

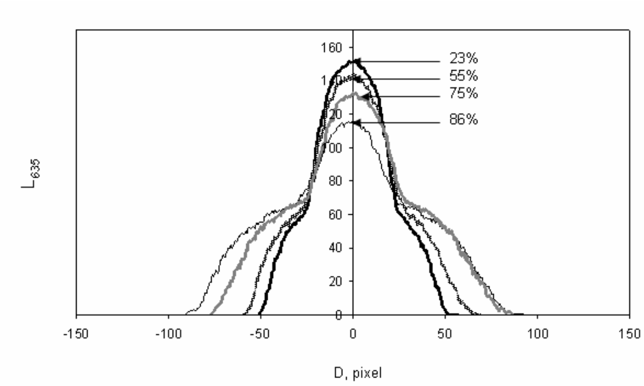

Fig. 2. Light luminescence at 635 nm (L635) versus scattering diameter (D) in apple tissue at different moisture content.

Each curve represents the average of five apples slices at certain moisture content during drying. A difference in behavior between light luminescence, expressed by the gray values, and the scattering diameter at 635 nm was observed at different levels of moisture content. As the scattering diameter decreased, the peak of luminescence became narrower and higher luminescence values were obtained. Highest luminescence was found at 23 % moisture content.

Relationship between quality parameters and laser light backscattering

Calibration equations between quality parameters and laser light backscattering properties are shown in Figures 3 and 4.

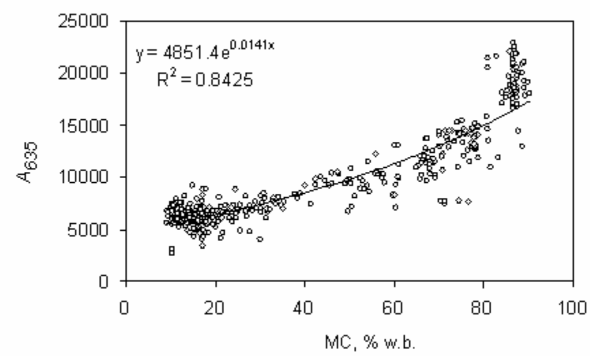

Fig. 3. Relationship between moisture content (MC) with backscattering area (A635)

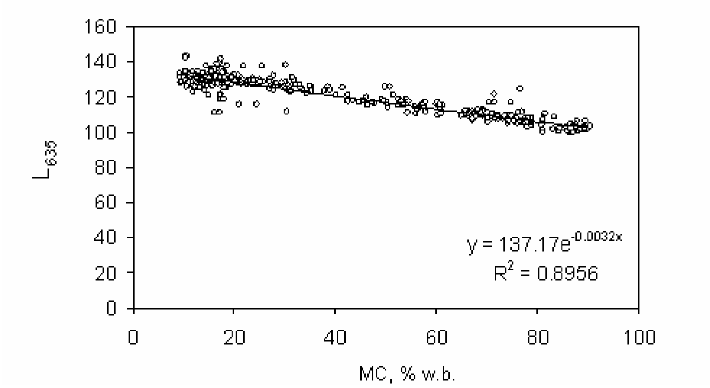

Fig. 4. Relationship between moisture content (MC) with backscattering area (A635)

Exponential models were applied to the relationship between backscattering area and moisture content yielding values of (R^2=0.84) Linear models were applied to analyze the relationship between light luminescence and moisture content. The relationship between light luminescence and moisture content showed the highest correlation coefficient (R^2=0.89). A decrease in moisture content caused a reduction in visible photon scattering and, as a consequence, an increase in inner luminescence due to enhanced light absorption in the apple tissue. It was also possible to observe a reduction in the backscattering area at lower moisture content, which might have been determined by diminished light propagation in the tissue. As expected, fresh slices with high moisture contents caused higher dissemination of the photons which increased the backscattering area. This is consistent with the fact that the surfaces of fresh slices had completely opened pores and were saturated with water, meaning that the tissue could be easily penetrated by light. This might explain the broader photon backward distribution within the tissue of samples at higher moisture contents. When moisture is reduced in fruit tissue, air replaces water in intracellular spaces. Reduced solid/water interfaces increase absorption due to the higher density of the solid material (Bobelin ***et al.*** 2010). As a consequence, less refraction and more absorption give a smaller backscattering area. Also, removal of water can induce closer packing of the tissue components, making the tissue structure more opaque. This could also result in reduced scattering. On the contrary, photon absorption at 635 nm was found not to be suitable for predicting changes in hardness during apple drying. This might be explained by the fact that as the slices became harder, tension was developed with deformation of internal structures and reduction in size and numbers of cells causing the formation of large cavities (Lewicki and Jakubczyk, 2004). Due to this phenomenon, light will not be propagated into the lateral areas and its tissue penetration should be regarded as noise. Moreover, since firmness is related to the shrinkage (Talla ***et al.*** 2004), some of the incident photons strike the shrunken surface more than once before being reflected (Gunasekaran ***et al.*** 1985) causing distortion of the backscattering profiles. Additionally, when light is scattered from the surface to the detector, the surface area is enlarged and less light travels through the surface to be detected by the camera (Zude ***et al.*** 2008). This does not mean that the scattering coefficient is reduced, but that the apparent light reaching the camera is altered. More detailed study with microscopic analysis might be able to detect changes in surface properties and to confirm the impact of these changes on the scattered light.

Prediction of moisture content

Results of moisture content prediction abilities of calibration models for apple drying at the three temperatures are presented in Figures 5 and 6. Validation analysis gave a lower SECV (9.8) for light luminescence than for backscattering area (SECV=11.6). Thus, the best laser parameter for estimating moisture content was luminescence.

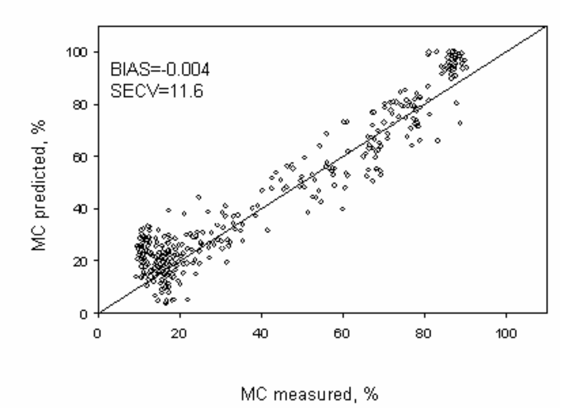

Fig. 5. Prediction models for moisture content (MC) based on backscattering area

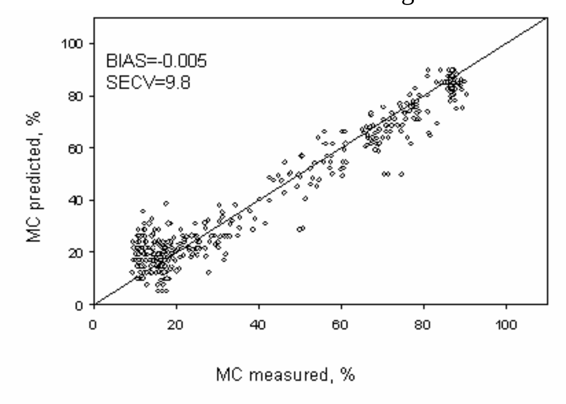

Fig. 6. Prediction models for moisture content (MC) based on Light luminescence

4. CONCLUSIONS

The described optical technology based on laser backscattering represents an innovative and reliable method for rapid and non-invasive monitoring of drying processes. Validation results showed that backscattering area and light luminescence can accurately predict changes in moisture of apple at different drying stages. Although the present results can provide the basis for future development of in-line monitoring of quality during drying of food products, additional studies are awaited to assess the influence of different thickness on the scattered and transmitted light from the sample tissue.

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