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Multi-sensor approach to improve optical monitoring of papaya shrinkage during drying

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This study aimed to assess the feasibility of a multi-sensor approach for predicting shrinkage of papaya during drying using computer vision methods in combination with optical scattering analysis of light at 650 nm. The top-side area and total surface area derived from computer vision were analyzed, while the illuminated area and light intensity from optical scattering images were used to interpret photon migration in the fruit tissue. The relationship between moisture content and shrinkage in terms of volume and area reduction during drying was satisfactorily explained by a linear model. The results demonstrated that the prediction of papaya shrinkage during drying from top and total surface areas of the sample was possible, but can potentially be improved. Multivariate correlations of computer vision parameters and optical scattering properties showed the enhanced performance for shrinkage prediction. This multi-sensor approach could possibly be applied as a fast, accurate and non-invasive technique for in-line quality control to monitor shrinkage in the production of dried fruits.

1. Introduction

Papaya is an important fruit crop which serves as a good source of vitamins A and C as well as calcium, potassium, and magnesium. From a biological point of view, papaya is a crop that is subject to considerable post-harvest losses due to rapid senescence that causes high perishability. Consequently, postharvest procedures are useful for producing papaya products with extended shelf life. Drying is one of the most widely used preservation methods that allows for greater flexibility in the availability and marketability of products, regardless of high production volume. However, drying can provoke numerous undesirable changes in materials in terms of structural, physicochemical, and nutritional properties, especially as commonly implemented by hot-air convective drying.

Mechanical characteristics such as density, porosity, volume, shape, and surface hardness are highly affected by drying and are considered among the most important quality attributes of dehydrated products related to consumer acceptance. However, relationships between moisture, temperature, and mechanical properties during drying of food materials are decidedly complex (Devahastin and Niamnuy, 2010), with viscoelastic properties of foodstuffs affecting drying rate and final qualities (Bhandari and Howes, 1999). Overall, much research has been conducted to better understand the dynamics of structural properties of dehydrated products by applying concepts of plasticization and glass transition (Alzamora et al., 2008; Aregawi et al., 2013; Martynenko and Janaszek, 2014; Telis et al., 2005) as well as studying microstructure (Mayor et al., 2005; Xu and Li, 2015).

During drying, volume shrinkage occurs in products when the viscoelastic matrix contracts into the space which was previously occupied by the water (Aguilera, 2003; Yadollahinia et al., 2009). Many studies have reported a linear correlation between shrinkage and moisture content during convective drying of foods (Khraisheh et al., 2004), also in specific fruits such as apple (Moreira et al., 2000) and mango (Hernández et al., 2000). Shrinkage in those studies has been determined by direct measurements with a caliper or micrometer, otherwise by changes in related parameters such as porosity and density as measured by displacement. However, such methods require manual involvement and are not efficient and

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practical approaches for in-line measurements. Meanwhile, the application of image processing techniques is one of the most promising methods with potential for area, perimeter, diameter and shape evaluation and quantification for fruits and vegetables. Du and Sun (2004) reported that computer vision provides more versatile, reliable and faster ways to measure the dimensions of many foods than performed by manual determination. With respect to monitoring of drying processes, various studies have been conducted using such techniques. Mulet et al. (2000) successfully investigated the geometric changes during drying of potato and cauliflower by image analysis. Fernández et al. (2005) also applied image processing to measure area, perimeter, average radius, roundness and Feret diameter of apple discs during drying. Yan et al. (2008) showed that computer vision was applicable to measure the diameter and perimeter of banana, mango and apple during drying. They also observed that the change of diameter and perimeter was found to be a second order polynomial function of moisture content.

Increasingly, laser light scattering, a sensor-based technique, has been used as an alternative non-invasive method for detecting quality of agricultural products (Mollazade et al., 2012), including moisture content, firmness and soluble solids content of fruits. When a visible light hits the translucent biological materials, only a small fraction of photons are reflected at the fruit surface, while the rest enters into the fruit tissue and undergoes absorption, transmission, or scattering. Commonly, absorption and scattering are two phenomena that occur as light interacts with biological materials which provide a large amount of useful information about the physicochemical properties. Since optical properties are wavelength-dependent, absorption in fruits is related to the chemical constituents such as soluble solids, moisture and pigments. Scattering of light is a result of the projection of photons at different angles which not only depends on absorption, but also physical properties such as density, cell size, and extra- and intracellular matrices of fruit tissue. Laser light scattering systems have been reported to be energy-saving and economic devices operating with quantitative information when compared to near-infrared reflectance spectroscopy which allow for simultaneous prediction of quality parameters during food processing (Adebayo et al., 2016). With respect to fruit quality, Qing et al. (2007) predicted soluble solid content and firmness of apple using laser diodes at five wavelengths between 680 and 980 nm. Romano et al. found that the optical scattering measurements were suitable for predicting quality changes during drying in a range of fruit products (Romano et al., 2012, 2011, 2016).

Although shrinkage is probably one of the most comprehensively studied processes in products during drying, modelling is largely empirical through the use of equations relating changes in shape, size, or volume to the moisture content of a specific product under a defined drying process. Recently, Udomkun et al. (2014b) investigated the feasibility of optical scattering analysis at three wavelengths (532, 650, and 780 nm) for predicting moisture content changes and shrinkage of papaya during drying. Nevertheless, study is still required in order to model processes for design and control of drying operations and product quality. Presently, there are many studies of non-invasive optical-based technologies for determining physicochemical quality of fruits during sorting, grading, packaging, and transportation. However, no previous studies have assessed the possibility of multi-sensor approaches for improvement of optical monitoring fruit shrinkage during drying. Therefore, the objectives of this study were to investigate the possibility of the combined image processing techniques for shrinkage determination of papaya during drying.

2. Materials and methods

2.1. Sample preparation

Thai papaya (*Carica papaya* L. cv. Pluk Mai Lie) harvested from a commercial orchard in Nakhon Nayok province, Thailand, was obtained from a local import company. Fruits of uniform shape and weight (1.0 ± 0.2 kg/fruit) at three quarters of ripening stage (70 ± 10% of yellowness skin) were selected. Before preparation for drying, fruits were stored under refrigeration at a temperature of 10 ± 1 °C and relative humidity (RH) of 20–35%. Storage time was never more than 5 days. For sample preparation, consistent initial moisture content X_0 (4.6 ± 0.4 kg kg^{-1}), soluble solids content (10.0°±0.5° Brix), titratable acidity (0.14 ± 0.02 g citric acid·100 g^{-1}) and pH (5.2 ± 0.2) were ensured. Fruits were hand-peeled and cut into slabs of 20 × 30 × 20 mm using a specially designed stainless steel cutter.

Fruit slabs were osmotically treated according to the procedure described by (Udomkun et al., 2014a). Samples were rinsed with fresh water and then soaked in 25 g L^{-1} calcium lactate solution for 1 h under controlled temperature (20°±2 °C), then blanched at 60°±2 °C for 1 min. Subsequently, they were immersed in 30° Brix osmotic solution at a starting temperature of 60°±2 °C and allowed to stand at room temperature for 6 h. The osmotic solution was prepared by dissolving 99.9% refined sucrose in water to obtain the required concentration and then pH was adjusted to 4.0 using citric acid. The weight ratio of osmotic solution to fruit samples was 1:1. After removal from the solution, the samples were rinsed with tap water, drained and blotted with absorbent paper to remove the surface water before drying.

2.2. Convective hot-air drying

Drying experiments were carried out using the through-flow chamber of a high-precision laboratory dryer designed at the Institute of Agricultural Engineering, Tropics and Subtropics Group, at University of Hohenheim in Stuttgart, Germany. Detailed descriptions of the experimental drying system have previously been given (Argyropoulos et al., 2011; Udomkun et al., 2015). Seventy-two samples were evenly distributed on a round perforated tray and convectively dried at temperatures of 50°, 60°, 70° and 80 °C, specific humidity of 25 g kg^{-1} of dry air. A uniform air stream flowing perpendicular to the samples was maintained constant at 0.5 m s^{-1}. During the drying process, six samples were intermittently removed from the dryer for shrinkage and optical measurements. Papaya slabs were dried until the moisture content X reached 0.16–0.18 kg kg^{-1} with a corresponding water activity of 0.5 ± 0.05. Experiments were performed in three independent triplicates.

2.3. Specific volume and shrinkage measurements

The toluene displacement method was applied to measure the volume of papaya cubes (Yan et al., 2008). From this method, sample shrinkage was calculated. A flask was calibrated using distilled water and the volume was determined. The density of toluene, determined by weighing the flask full with toluene, was found to be 0.8686 g cm^{-3}. One cube of sample was weighed and transferred into a flask half-filled with toluene, and then, the flask was completely filled with toluene. One piece of fruit was used each time and experiments were performed in triplicate. Results were obtained from mean values.

The volume of sample (V) was calculated as: