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Research Paper

Hyperspectral imaging for the determination of potato slice moisture content and chromaticity during the convective hot air drying process

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Hyperspectral imaging (HSI) was utilised for the determination of moisture content of potato slices with three thicknesses (5 mm, 7 mm, 9 mm) at three drying temperatures (50 °C, 60 °C, 70 °C) during convective drying in a laboratory hot air dryer. The Page, thin-layer drying model was found better to explain the drying kinetics with a fitting accuracy of R^2 (0.96–0.99) and lowest reduced Chi-square (0.00024–0.00090), Root mean square errors (RMSE) (0.014–0.026), and relative percentage error (1.5%–5.1%) under the used drying conditions. Spectral data were analysed using partial least squares regression (PLS) analysis, a multivariate calibration technique, alongside Monte Carlo Uninformative Variable Elimination (MCUVE-PLS) and competitive adaptive reweighted sampling (CARS-PLS). The feasibility of both moisture content and CIELAB prediction with a reduced wavelength set from the Visible near-infrared (VNIR) region (500–1000 nm) was investigated with these three models. The PLS model (R^2 = 0.93–0.98, RMSE = 0.16–0.36 and the lowest number of optimal wavelengths = 6, for all drying conditions) was found suitable to implement for the moisture visualisation procedure. Potato chromaticity was also shown to be predictable during drying using a similar number of wavelengths, with PLS models for CIELAB a* performing well (R^2 = 0.91–0.65, RMSE = 0.61–1.78). PLS Models for CIELAB b* more variably (R^2 = 0.91–0.62, RMSE = 2.16–4.42) due to potato colour mainly varying along this axis. The current study showed that hyperspectral imaging was a useful tool for non-destructive measurement and visualisation of the moisture content and chromaticity during the drying process.

1. Introduction

Worldwide annual potato production accounts to about 365 million metric tons, ranking it as the most important crop (FAOSTAT, 2012). The consumption rate of processed potato products has increased over the last 30 years due to changes in lifestyle trends which has ultimately increased the importance of quality assessment of raw and processed products

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Nomenclature

DN	Dark noise
λ	Wavelength
MDN_λ	Mean value at the specified wavelength $\lambda$of the calculated dark noise (DN)
I_{DN_λ}	Raw DN value at specified wavelength at a given pixel
$I(\lambda_{x,y})$	Irradiance spectrum
$W(\lambda)$	Average illumination spectrum
$R(\lambda_{x,y})$	Relative reflectance spectrum
VNIR	Visible near-infrared
PLS	Partial Least Squares regression
MCUVE	Monte Carlo Uninformative Variable Elimination
CARS	Competitive Adaptive Reweighted Sampling
HSI	Hyperspectral imaging
MR_{exp}	Experimental moisture ratio
MR_{pre}	Predicted moisture ratio
RMSE	Root mean square errors
χ^2	Reduced Chi-square
N	N number of observations
n	n number of constants

(Rady, Guyer, & Lu, 2015). For potato processing, drying is one of the most widely used preservation methods.

In the potato drying industry, the final quality is strongly influenced by the moisture content of the product. Dried potatoes can be used to make flakes, flour, confectionaries and more. Convective air drying is the most common drying method in the food industry (Ionuţ, Ioan, Petru, & Vasile, 2013); however, it causes undesirable thermal degradation of the product quality (Chen & Mujumdar, 2008). The effect of different drying temperatures, air flow rates and humidity conditions are the main factors affecting the drying rate. The rates of shrinkage and colour change are also directly related to the moisture content (Amjad, Hensel, Munir, & Esper, 2015). Therefore, during the drying process, at different time intervals, exact estimation of the moisture content is very important to develop effective relationships between quality attributes (e.g. chromaticity) and moisture content of the product for the optimisation of the drying process (Amjad, Hensel, Munir, Esper, & Sturm, 2016). These relationships would help to develop algorithms to control the process conditions itself as most of the research in the food drying sector is still focused on the understanding of the drying mechanisms and product quality rather than on dynamic control of the operation.

Different destructive, or interruptive (periodic weighing) and non-destructive (load cells, IR-sensors) techniques have been reported and are currently in use for the determination of moisture contents during the food drying process. Instrument errors are inevitable even in the commonly used non-destructive approaches. Nowadays, food industries maintain quality and safety standards to meet customer demand (Pu, Feng, & Sun, 2015). Although spectrometers are a useful tool they are unable to predict the moisture distributed unevenly due to their spot measurement nature (Wu & Sun, 2013). Therefore, the use of hyperspectral imaging (HSI) for agricultural applications has been increased in recent years. A relative short measurement time, minimal sample preparation and it being a standalone non-destructive method are the advantages of this imaging system compared to the chemical and physical analytical methods. The quality and safety related assessments of fruits and vegetables have been reported by many researchers with successful applications of hyperspectral imaging. These applications include defect detection on apples (Yang, Kim, & Chao, 2012), oranges (Li, Rao, & Ying, 2011), strawberry (Nagata, Tallada, Kobayashi, & Toyoda, 2005), cucumber (Cheng et al., 2004), and tomato (Cho et al., 2013), maturity detection in peach (Herrero-Langreo, Fernández-Ahumada, Roger, Palagós, & Lleó, 2012) and grape seeds (Rodríguez-Pulido et al., 2013), moisture estimation in banana (Rajkumar, Wang, Eimasry, Raghavan, & Gariepy, 2012), insect damage in mung bean (Kaliramesh et al., 2013) and vegetable soybean (Huang, Wan, Zhang, & Zhu, 2012), glucose estimation in banana (Tarkosova & Copikova, 2000) and carrot (Schulz, Drews, Quilitzsch, & Kruger, 1998). All of the above research into defect detection utilised chromaticity features to detect defects. Chromaticity gives a visual cue to not only defects in agricultural produce, but also to perceived consumer quality. As such chromaticity of produce must be monitored and managed during processing.

In the case of potato, the reported uses of hyperspectral imaging technique have mainly focused on the fresh produce for the determination of starch (Trong, Tsuta, Nicolai, De Baerdemaeker, & Saeys, 2011), moisture content with and without skin (Elbatawi, Ebaid, & Hemeda, 2008; Singh, 2005), sugar (Mehrubeoglu & Cote, 1997), sucrose, protein, glucose, fructose (Hartmann & Buning-Pfaue. 1998), blackheart detection (Zhou, Zeng, Li, & Zheng, 2015), and specific gravity (Scanlon, Pritchard, & Adam, 1999). Qiao, Wang, Ngadi, and Baljinder (2005) estimated water content and the weight of potato tubers using HSI and found the wavelength range of 934–997 nm best for moisture prediction in tubers. However, there has been no literature reported on the use of HSI for potato moisture measurement during the drying process for determination of process stop time. The successful application of this technique during the drying process would help to meet the quality standards. Therefore, the objectives of the study were:

- Determine the potential of hyperspectral imaging for the determination of moisture content as well as chromaticity of potato slices of different thicknesses under different drying temperatures.
- Find the drying model that best describes the drying kinetics.
- Estimate the most informative wavelengths for moisture content and chromaticity prediction using different algorithms based on HSI data.
- Produce moisture prediction maps of potato slices based on optimally selected model.

2. Materials and methods

2.1. *Sample preparation*

The experiments were carried out using locally available potatoes (*Solanum tuberosum* L. var. Anuschka). Potatoes coming