BIOSYSTEMS ENGINEERING 156 (2017) 108–119

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/issn/15375110

Research Paper

Combined hot-air and microwave-vacuum drying for improving drying uniformity of mango slices based on hyperspectral imaging visualisation of moisture content distribution

Yuan-Yuan Pu, Da-Wen Sun*

Food Refrigeration and Computerized Food Technology (FRCFT), School of Biosystems and Food Engineering, Agriculture and Food Science Centre, University College Dublin, National University of Ireland, Belfield, Dublin 4, Ireland

ARTICLE INFO

Article history:
Received 6 July 2016
Received in revised form
6 January 2017
Accepted 18 January 2017

Keywords:
Hyperspectral imaging
Hot-air
Microwave-vacuum drying
Moisture content
Visualisation
Uniformity

Drying uniformity is one of the most important indicators in evaluating a drying technique as well as the final quality of dried products. In the current study, three drying approaches (hot-air drying (HAD), microwave-vacuum drying (MVD), and the combined method (HAD + MVD)) were applied to dehydrate mango slices. During the HAD + MVD process, the time required for hot-air drying was determined in terms of colour variations during hot-air drying. With the help of hyperspectral imaging in conjunction with multivariate data analysis and image processing, the moisture content distribution on mango slices subjected to different drying methods was visualised. Results showed a non-uniform drying property for mango slices dried by HAD or MVD individually, where HAD-dried samples had a higher moisture content in the centre but MVD-dried samples showed the opposite result. Drying uniformity was improved when HAD and MVD were combined, which produced dried products with an even moisture distribution. Mango slice samples dried by HAD + MVD showed a porous structure and a high percentage of colour retention. The current study led to the development of an effective combined HAD + MVD technique for enhancing drying uniformity for the industry.

1. Introduction

Like cooling (Hu & Sun, 2000; Mc Donald & Sun, 2001; Sun, 1997; Sun & Brosnan, 1999; Sun & Hu, 2003; Sun & Wang, 2000; Wang & Sun, 2002a, 2002b, 2004; Zheng & Sun, 2004) and freezing (Kiani, Zhang, Delgado, & Sun, 2011), drying is one of the most commonly used thermal techniques to preserve food and agricultural products (Cui, Sun, Chen, & Sun, 2008; Sun & Woods, 1994). During the drying process, heat is transferred by convection, conduction, radiation, or their combination (Arun, 2006). Hot-air drying (HAD) is a typical convective drying method that has been largely applied for the

* *Corresponding author*. Fax: +353 1 7167493.
E-mail address: dawen.sun@ucd.ie (D.-W. Sun).
URL: http://www.ucd.ie/refrig, http://www.ucd.ie/sun

http://dx.doi.org/10.1016/j.biosystemseng.2017.01.006

drying of a variety of fruits and vegetables and its by-products (Fernandes, Rodrigues, Law, & Mujumdar, 2010; García-Martínez, Igual, Martín-Esparza, & Martínez-Navarrete, 2012; Saxena, Maity, Raju, & Bawa, 2010; Uribe et al., 2009, 2012). In a conventional hot-air drier, dried air is electrically heated and then forced to flow through the drying material. The thermal energy supplied by the hot-air is transferred from the surrounding environment to the surface of the material by convection, and then to the interior of the material by conduction. Generally, moisture content of the inner part is higher than on the surface due to poor heat transfer and low moisture migration through the materials, especially for low-porosity materials (Labuza & Hyman, 1998). As a result, total drying time is prolonged to ensure the entire product achieving a specific average moisture content. Increasing hot-air temperature or flow rate could be an alternative in order to improve drying efficiency (Giri & Prasad, 2007; Wang et al., 2014). However, an increase of energy consumption and a deterioration of product quality occur when products are subjected to higher temperatures for a long time.

Microwave drying is a volumetric drying method that can be used to enhance the transportation of heat and moisture inside the drying products. Dielectric materials (e.g., food and textiles) absorb high frequency (2.45 GHz is commonly used in domestic microwave ovens) microwave energy and transform it into heat. The heat is mainly generated by internal 'molecular friction' of those dipolar molecules (e.g., water) present in the material as they attempt to realign themselves with external oscillating electric fields (Meda, Orsat, & Raghavan, 2005). Internal heating results in water evaporation and subsequently generates a large amount of pressure. It is the interior pressure gradient that drives moisture outward to the surface of the material, which speeds up the drying process. The use of vacuum in microwave drying, called microwave-vacuum drying (MVD) (Cui, Xu, & Sun, 2003, 2004a, 2004b), helps to further increase drying rate and lower the drying temperature due to that fact that vacuum enables moisture to evaporate at a lower temperature, thus maintaining good product quality particularly for products with heat-sensitive components (Bórquez, Melo, & Saavedra, 2014). Nevertheless, a major issue to be addressed when microwaves are involved in drying is the non-uniformity of heating, affecting the uniformity of the final product (Cha-um, Rattanadecho, & Pakdee, 2009; Hossan, Byun, & Dutta, 2010; Pitchai, Birla, Jones, & Subbiah, 2012).

A good drying system is evaluated by its efficiency in removing the moisture content of products to a certain level and at the same time lowering the quality degradation that occurs in any drying process. However, drying uniformity is an important indicator in assessing the drying method as well as the final dried product. Uniform drying refers to two aspects of the dried product quality, one is that there should be minimal quality differences among samples in the drier, and the other is that an even drying result within individual samples should be obtained. The effect of non-uniform drying among different samples could be reduced by improving the uniformity of microwave distribution in the cavity using a mode stirrer and a rotating plate, or re-organising the location of samples (Li, Wang, & Kudra, 2011). However, non-uniform drying arising from the sample itself (e.g., size, shape, dielectric properties of different components) is a more challenging problem to solve (Venkatesh & Raghavan, 2004; Vilayannur, Puri, & Anantheswaran, 1998), as these sample properties change during the drying process. Due to the opposite heating mechanisms of hot-air drying and microwave-vacuum drying (Hu, Zhang, Mujumdar, Xiao, & Jin-cai, 2006), the integration of both two drying processes could be an effective way to achieve better drying results in terms of colour, texture, and nutrition retention. Previous research has found that applications of combined HAD and MVD were successful in drying carrots (Arikan, Ayhan, Soysal, & Esturk, 2011), garlic slices (Calín-Sánchez, Figiel, Wojdyło, Szarycz, & Carbonell-Barrachina, 2013), sour cherries (Wojdyło, Figiel, Lech, Nowicka, & Oszmiański, 2013) and others (Calín-Sánchez et al., 2015; Chong, Figiel, Law, & Wojdyło, 2014; Esturk, 2012).

The non-uniformity of temperature distribution in samples subjected to microwave treatment can be visualised using infrared thermal imaging (Manickavasagan, Jayas, & White, 2006) and magnetic resonance imaging (Knoerzer, Regier, Hardy, Schuchmann, & Schubert, 2009). However, these techniques only provide temperature information on the samples. For product quality control and food safety assurance, it is important and beneficial that the distribution or variation of quality attributes such as moisture content in the samples can also be visualised during the drying process. With the integration of imaging or computer vision (Du & Sun, 2005; Jackman, Sun, & Allen, 2009; Wu & Sun, 2013a) and spectroscopy techniques, hyperspectral imaging (HSI) enables quality information associated with spectral responses to be displayed in a spatial domain (image), and in recent decades, HSI has been extensively studied for its capability in fast scanning, non-destructive detection and visualisation of quality concerns in agricultural and food products (Barbin, Elmasry, Sun, & Allen, 2012, 2013; Elmasry, Barbin, Sun, & Allen, 2012; ElMasry, Sun, Allen, 2013; Feng et al., 2013; Feng & Sun, 2012, 2013; Kamruzzaman, ElMasry, Sun, & Allen, 2012, 2013; Liu, Sun, & Zeng, 2014; Lorente et al., 2011; Pu, Feng, & Sun, 2015; Wu & Sun, 2013b). However, information on using HSI for evaluating microwave vacuum drying processes is limited. Huang, Wang, Zhang, and Zhu (2014) investigated visible reflectance HSI for the prediction of colour and moisture content of vegetable soybean in the process of microwave-assisted pulse-spouted bed vacuum drying and showed a better prediction performance for both moisture content and colour, with correlation coefficients (R_p) of 0.971 and 0.862, respectively. However, drying uniformity of final products was not mentioned in their study. On the other hand, Pu and Sun (2015) were the first to use HSI to study the non-uniformity of MVD, who utilised reflectance visible and near-infrared HSI to investigate moisture distribution of mango slices dried by intermittent microwave-vacuum drying, and the effects of sample shapes on moisture uniformity during MVD were also evaluated (Pu & Sun, 2016). These studies of Pu and Sun (2015, 2016) suggest that an effective approach on improving the drying uniformity during microwave-vacuum drying is needed.