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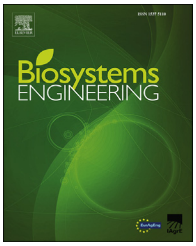

Research Paper

Non-destructive investigation of cellular level moisture distribution and morphological changes during drying of a plant-based food material

Mohammad M. Rahman, Mohammad U.H. Joardder, Azharul Karim[*]

School of Chemistry, Physics and Mechanical Engineering, Faculty of Science and Engineering, Queensland University of Technology, Brisbane, Queensland, Australia

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This study investigates the complex microstructural changes and cell-level water transportation in plant-based food materials during drying, using X-ray micro-computed tomography (X-ray μCT). The investigations were performed on apple tissue to uncover the cellular level moisture distribution and the structural changes during convective drying at 50 °C, 60 °C, and 70 °C. Image analysis revealed that significant changes occurred in moisture content, and cell and pore size distribution with drying time and temperature. The moisture content determined using the X-ray μCT images was compared with that determined by the electronic moisture analyser (EMA) and good agreement was found. The results show a strong relationship between drying temperature, pore formation and deformation of the food material. At high drying temperature, the pore formation increased, which led to reduced shrinkage of the food material. The porosity of a sample of dried apple increased by 35% as drying temperature increased from 50 °C to 70 °C. However, a significant amount of cell rupture was observed during drying at the higher temperature. The cellular level moisture distribution profile confirmed that a traceable amount of water was still present in the centre cells of the tissue although the sample was deemed dried from the bulk moisture analysis. The findings of this study substantially enhance our understanding of instantaneous cellular level moisture distribution in a food sample over the time of drying.

1. Introduction

The principle purpose of food drying is to remove moisture from the food material to increase its shelf life while maintaining the quality of the product. Drying of plant-based food materials is a complex process as it involves simultaneous heat and mass transfer and micro-level changes (Kumar et al., 2012; Rahman, Mekhilef, Saidur, Mustayen Billah, & Rahman, 2016). The microstructural changes critically influence the overall transport process and the physical behaviour of food materials (Rahman, Joardder, Khan, Nghia, & Karim, 2016). Moreover, moisture transport through the intercellular spaces, and cells and cell walls of food materials occurs at the

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[*] *Corresponding author.*
E-mail address: azharul.karim@qut.edu.au (A. Karim).

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micro-level (Aguilera, Chiralt, & Fito, 2003; Rahman et al., 2016). Therefore, it is essential to understand the micro-level transport mechanism and the microstructural changes that take place during drying.

Plant-based food materials consist of cellular tissues, and the tissue consists of cells and intercellular spaces (Joardder, Karim, Kumar, & Brown, 2015; Joardder, Kumar, Brown, & Karim, 2015). A major component of plant-based food materials is the water that is distributed in the microstructure. There are two types of water in the food microstructure, which are classified based on their spatial locations. These are free water (intercellular water) and bound water (intracellular water) (Khan, Wellard, Nagy, Joardder, & Karim, 2017). The bound water is located inside the cells whereas the free water is located in the intercellular spaces. Research has shown that about 85%–95% of the water is bound in food materials, and the rest of the water remains in the intercellular spaces and cell walls (Khan, Wellard, Nagy, Joardder, & Karim, 2016). The transport of bound and free water govern the overall drying process (Rahman, Joardder, Khan, Nghia, & Karim, 2016), and therefore, it is crucial to understand the water characteristics and their effect on the evolution of food microstructure in order to make an accurate prediction of energy requirement and the quality changes during food processing especially drying.

The transport of water inside food tissue can take three pathways during drying, namely symplastic, apoplastic and transcellular transport (Joardder, Kumar et al., 2015). When the sample has high moisture content, liquid water flows due to dominating capillary forces. The bound water has lower diffusivity than the free water when the cells are intact (Fanta et al., 2012). Therefore, the required energy for removing the bound water and free water from the food microstructure is different. Bound water removal also affects the microstructure of the food materials (Khan et al., 2017). Consequently, knowledge of exact proportion of free and bound water is important and an appropriate non-destructive means of bound water measurement is crucial as destructive methods lead to inaccurate measurements (Léonard, Blacher, Marchot, Pirard, & Crine, 2005).

There are several methods in the literature for determining cell-level water content in a fresh food sample, including differential scanning calorimetry, bioelectrical impedance analysis, dilatometry, thermogravimetric analysis, and nuclear magnetic resonance (NMR) (Khan & Karim, 2017). The different types of water content inside food materials during drying were determined by Khan et al (2016) using the NMR technique. However, the cell-wall structure, cellular water, and intercellular water distribution cannot be identified clearly by this method. Moreover, Khan et al.'s determination of various water contents relied on many assumptions. To date, no research has been conducted to investigate the distribution of cellular water (intracellular and intercellular water) during drying of food material.

It has been anticipated that the cell rupture takes place under certain drying conditions (Khan, Joardder, Kumar, & Karim, 2017; Khan, Wellard et al., 2017; Rizzolo et al., 2014). Cell rupture depends on internal thermal stress that first develops near the surface and gradually penetrates to the centre of the sample during convective drying (Khan, Joardder et al., 2017; Khan, Wellard et al., 2017). In other words, the entire food sample does not reach breakdown temperature at the same time. Therefore it is a logical assumption that the cells may collapse progressively from the surface to centre (Achanta & Okos, 1996; Askari, Emam-Djomeh, & Mousavi, 2009; Gumeta-Chavez et al., 2011; Khan, Joardder et al., 2017; Khan, Wellard et al., 2017; Rahman, Mustayen, Mekhilef, & Saidur, 2015; Riva, Campolongo, Leva, Maestrelli, & Torreggiani, 2005; Yang, Di, Jiang, & Zhao, 2010). Khan, Joardder et al., 2017; Khan, Wellard et al., 2017 reported that cells rupture at different stages of drying. However, this progressive rupture was assumed, based on the pattern of the intercellular water content. No clear evidence of cell rupture during drying was presented.

More complete microstructural information regarding the porosity and the cell rupture of plant-based food is required to improve the physical quality of dried food. Although the investigation of cellular level changes is critical to anticipate the overall shrinkage and porosity of the food materials, only a limited number of studies have been found that dealt with cellular level transport during drying (Joardder, Kumar et al., 2015; Karunasena et al., 2014; Khan, Joardder et al., 2017; Khan, Wellard et al., 2017). Most of the porosity measurement techniques reported in the literature (e.g. solid displacement method) are destructive and invasive (Joardder, Kumar et al., 2015; Joardder, Kumar, & Karim, 2017a, 2017b). Therefore these methods are not suitable to determine the instantaneous morphological changes during drying. The limitations of destructive and invasive methods justify the importance of non-destructive and non-invasive methods.

Khan, Joardder et al., 2017; Khan, Wellard et al., 2017 reported the NMR technique to be a suitable technique to uncover the cellular level water distribution. However, this technique produces a large amount of noisy data, and variations in cellular level water distribution cannot be readily identified. X-ray μCT has proved to be valuable in the study of plants and plant-based food materials, reflecting anatomical details of the entire tissue, especially the microstructure and the water distribution (Herremans et al., 2015; Mendoza et al., 2007). X-ray μCT is the most suitable technique to address the elucidation of the cellular level transport mechanism during food drying (Lim & Barigou, 2004; Rahman et al., 2016).

The earliest applications of computed tomography were in medicine. However, it has rapidly become a very useful tool in physics (Wildenschild, Vaz, Rivers, Rikard, & Christensen, 2002), biology (Momose, Takeda, Itai, & Hirano, 1996), materials science (Salvo et al., 2003) and multiscale engineering (Torre, Losada, & Tarquis, 2016; Wood, Zerhouni, Hoford, Hoffman, & Mitzner, 1995). Recently, micro-tomography, based on micro-focus X-ray sources, has become a relatively common tool for the characterisation of agricultural food products (Donis-González, Guyer, Pease, & Barthel, 2014; Schoeman, Williams, du Plessis, & Manley, 2016; van Dael et al., 2017) including apple (Almeida, Lancha, Pierre, Casalinho, & Perré, 2017; Diels et al., 2017; Si & Sankaran, 2016; Verboven et al., 2013), banana (Madiouli et al., 2011), mango (Cantre, Herremans, Verboven, Ampofo-Asiama, & Nicolaï, 2014), grains (Neethirajan, Karunakaran, Jayas, &