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A micro-level transport model for plant-based food materials during drying

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HIGHLIGHTS

- A novel microstructure based food drying model for plant based food material has been developed.
- The model can predict cellular level temperature and moisture distribution.
- The model is validated with experimental results obtained from X-ray micro CT experiemnts.
- The impact of cell and intercellular space in the drying process has been investigated.

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ABSTRACT

Microscale transport phenomena govern the overall transport mechanism during drying of plant-based food material. However, there is limited research available that considers micro-level transport phenomena during drying. The primary goal of this work is to develop a microscale drying model based on the heterogeneous microstructure of the plant-based food materials to predict cellular-level water transport mechanism during drying. The microstructure, which was used as a heterogenous computational domain for the model, was developed from scanning electron microscope images of food samples. Simulation results show that moisture transport and distribution are significantly affected by the characteristics of cells, the intercellular spaces and the cell walls. The predicted moisture profile from the developed model was compared with results obtained by X-ray microtomography (μCT), and a good agreement was found. The model and the experimental results also confirmed that a water gradient (2–3%) still existed in the dried sample around the walls of the cells that are located at the centre of the tissue. The micro-level temperature distribution in the cells and intercellular spaces was also successfully predicted. It was found that the air-filled intercellular spaces were heated faster than the cells during drying. Sensitivity studies were performed to investigate the influence of the key drying parameters on the micro-level transport process. The developed model accurately reflects the micro-level transport phenomena that occur during drying.

1. Introduction

Convective drying of plant-based food materials (fruits and vegetables) is a complicated process as it involves simultaneous heat and mass transfer. Moreover, the structure of plant-based food is complex, heterogeneous and porous (Mondragon et al., 2011). A sound understanding of the fundamental heat and mass transfer during drying is critical for the energy efficiency of the process and maximum retention of quality in dried food (Rahman et al., 2016). The moisture and temperature distributions in food materials contribute to the physical and chemical changes during drying. The fundamental transport process inside food material can be hampered significantly due to improper drying conditions (Duc Pham et al., 2017). The alternation of transport processes can lead to a reduction in the quality of the dried food product (Putranto et al., 2011). Therefore, accurate prediction of transport process in food material is very important in the drying. The transport process inside plant-based food material is strongly related to the cellular structure (Aguilera et al., 2003). Therefore, a transport model of the food drying process requires consideration of the cellular-level structural heterogeneity with the coupled heat and mass transfer process.

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1.1. Existing numerical models

Modelling of the transport process during drying involves the complex coupling of two different physics including heat transfer and mass transfer (Putranto et al., 2011). The mass transfer process involves transport of water and air (Kumar et al., 2016; Joardder et al. 2017). It is necessary to implement these two physics and their boundary conditions perfectly for obtaining a better prediction of moisture and temperature distribution (Perré, 2015). Numerous models of the drying process have been reported in the literature for various foods such as apple (Kumar et al., 2016), grapes (Khazaei et al., 2013), carrot (Cui et al., 2004), tomato (Movagharnejad and Nikzad, 2007), potato (Simal et al., 1994), mushroom (Rahman et al., 2016) and rice (Rahman et al., 2015). These models are developed in macroscale and considered food as a non-hygroscopic solid matrix where the cells are considered as surrounded by the free water (Dhall and Datta, 2011; Gulati et al., 2016). Moreover, the boundary conditions of the contributing physics cannot be implemented with accuracy in the macroscale model.

The water inside food materials is classified as intercellular water, intracellular water (bound water) and cell-wall water (Khan et al., 2016). Researchers have found that about 85–95% water is intracellular water and the rest of the water remains in the intercellular spaces and cell walls (Halder et al., 2011; Khan et al., 2016). The transport of bound and free water is crucial in the drying of food materials. The water transport phenomena inside food material are governed by the microstructural elements (i.e., cell, cell wall and intercellular space) found below the 200 μm range (Aguilera et al., 2000). Therefore, modelling heat and mass transfer of food drying remain incomplete unless the micro-level transport mechanism is considered. In this respect, formulation of the microscale model is required to describe the underlying transport phenomena that occur during drying. In the microscale model, the food is represented by the complex heterogeneous microstructure (Mebatsion et al., 2006; Rahman et al., 2016). The micro-level structural features of the plant-based food material have a great influence on the overall transport during drying (Aguilera et al., 2005; Aguilera et al., 2003; Mitchell et al., 2017; Rathnayaka Mudiyanselage et al., 2017). A microscale model was developed to study the water transport phenomena inside the fresh food (Fanta et al., 2014). Nevertheless, the model was restricted to a small range of moisture variation, and it did not consider the effect of temperature on moisture transportation in micro-level (Karunasena et al., 2014b). The variation of temperature and the moisture is considerably high in the drying process. The existing microscale models to date did not consider both contributing physics related to temperature and moisture variation (Rahman et al., 2016; Rathnayaka Mudiyanselage et al., 2017).

A particle-based approach, commonly known as mesh-free model, for simulating the micro-level changes in plant-based food material at different moisture level has been designed by various researchers (Karunasena et al., 2014a, 2014b; Van Liedekerke et al., 2011). The influence of the change of moisture content on the cell wall and the cell area was investigated by Karunasena et al., (2015). Smoothed particle hydrodynamics (SPH) and a discrete element method (DEM) were used in this study to simulate the cellular tissue of the plant-based food material. Cell mechanics was incorporated to simulate the cell-wall wrinkling due to moisture loss (Karunasena et al., 2015). It was a useful approach to analyse the deformation due to dehydration of the plant-based food material. However, the cellular-level transport process was not addressed in the study. Additionally, there is no conclusive agreement in the literature regarding this wrinkling effect. Recently significant cell-wall breakage instead of wrinkling due to drying of food material has been found in an experimental investigation (Khan et al., 2017). Therefore, further study of the microscale deformation phenomena in food material is required. The fundamental drying phenomena cannot be understood without knowing the microscale transport mechanism during the drying process (Rahman et al., 2016).

The existing microscale drying models consider the cellular structure of the plant-based food material as circular and ignore the influence of intercellular space on the transport process during drying. However, it has been reported that the cellular structure of the food materials does not have a regular shape and the presence of intercellular spaces have an influence on the moisture transport in food materials, and the presence of intercellular space plays a great role in the moisture transport in food materials (Abera et al., 2013; Aguilera and Lillford, 2008; Ho et al., 2011). Therefore, it is necessary to have a proper microstructural model of plant-based food material to analyse the transport process properly.

The limitations described above need to be addressed in order to obtain a mechanistic understanding of the fundamental physics involved in the convective drying process. Considering the limitations and the technical challenges of the existing models, there is a critical need to develop a microscale model based on the microstructure of plant-based food material that can handle the high temperature and moisture variation of the drying process.

(Rahman et al., 2016)

1.2. Objectives and organisation of the manuscript

The objectives of this study are: (1) to develop a novel microscale model based on the heterogeneous microstructure of the plant-based food materials to uncover the physics of the micro-level transport mechanism during drying; (2) to validate the developed model by performing an X-ray microtomographic experiment to study the moisture distribution in an apple slice; and (3) to perform a sensitivity analysis with the alternation of key parameters used in the proposed model.

The microstructure was generated from the scanning electron microscope (SEM) image as it provides very detail 2D structural information. As the focus of this work is to develop a heterogeneous 2D microscale model the SEM image is the most suitable option to generate the computational domain. To the best of our knowledge, this is the first attempt to consider heterogeneous food microstructure for developing a convective drying model. The remainder of the article proceeds as follows: first, the method of obtaining the microstructure based on the microscopic image is discussed. This is followed by the development of a coupled heat and mass transfer model which is capable of accounting micro-level transport process inside food materials during drying. Then, the experimental results of cellular-level moisture obtained by X-ray microtomography (μCT) are discussed and compared with the simulated result for the validation of the model. Finally, the micro-level temperature distribution at different stages of drying will be analysed.

2. Development of image-based microstructural geometry for modelling

The microstructure of apple is composed of parenchyma cells, which consist of thin walls also known as cell walls and intercellular spaces known as pores (Abera et al., 2013). Mebatsion et al. (2006) developed the microstructure of plant-based food materials based on the Voronoi tessellation algorithm. However, the accuracy of the Voronoi tessellation algorithm is poor, which is a major drawback of this approach (Pieczywek et al., 2011). Moreover, the process was time-consuming as well as complex. Later, Abera et al. (2013) developed a numerical code to overcome the drawback of