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Thermophysical properties of raw, hot-air and microwave-vacuum dried cranberry fruits (*Vaccinium macrocarpon*)

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The aim of this study was to compare the thermal properties of cranberry fruits measured with a thermal probe with the values calculated based on the chemical composition of raw, hot air convective dried (HACD, 80 °C) and microwave-vacuum dried (MWVD, microwave power density of 0.75 W g^{-1}, absolute pressure of 4–6 kPa) cranberry fruits. The influence of the drying technique on the thermophysical properties of cranberries was also evaluated. Dried cranberries were characterised by lower values of thermal conductivity and specific heat, and higher thermal diffusivity than raw fruits. The measured values were as follows: thermal conductivity - 0.248, 0.066 and 0.054 W $m^{-1}\cdot K^{-1}$, specific heat - 3509, 2288 and 1922 J kg^{-1} K^{-1} for raw, HACD and MWVD cranberries, respectively. The respective calculated values were as follows: thermal conductivity - 0.231, 0.068 and 0.053 W $m^{-1}\cdot K^{-1}$, specific heat - 3709, 1922 and 1953 J kg^{-1} K^{-1}. The measured values of thermal diffusivity were 1.06×10^{-7}, 1.08×10^{-7} and 1.23×10^{-7} m^2 s^{-1}, whereas the calculated values were 1.22×10^{-7}, 1.54×10^{-7} and 1.37×10^{-7} m^2 s^{-1} for raw, HACD and MWVD fruits, respectively.

1. Introduction

Cranberries (*Vaccinium*) are cultivated in North America, Europe and Northern Asia. Cranberry fruits are a source of bioactive substances such as anthocyanins, flavonols, flavonoids, proanthocyanidins (PAC), vitamins (A, C, B, E-groups), sugars (glucose, sucrose, fructose), minerals (i.a. sodium, potassium, phosphorus, calcium, magnesium, iron, manganese) and organic acids (Chen & Martynenko, 2017; Oszmiański, Wojdyło, Lachowicz, Gorzelany, & Matłok, 2016). Due to their composition and high nutritional value, cranberries deliver numerous health benefits. Cranberry fruits have antioxidant and antimicrobial properties, they inhibit the growth of yeast, Gram-negative bacteria and other pathogens (Harich, Maherani, Salmieri, & Lacroix, 2017). Cranberries have been found to alleviate gastrointestinal, cardiovascular and neurological disorders, help regulate blood glucose levels, and reduce the risk of cancer (Chen & Martynenko, 2017; Harich et al., 2017; Jeszka-Skowron, Zgoła-Grześkowiak, Stanisz, & Waśkiewicz, 2017). Fresh cranberries have an astringent, tart taste and high moisture content. Cranberry fruits can be dried or sweetened to extend their shelf life and modify their taste. They can be added to cereals and snacks (Chen & Martynenko, 2017; Jeszka-Skowron et al., 2017).

Cranberries can be dried to reduce their moisture content and maintain quality. Hot air convective drying (HACD) was used by Dorofejeva and Rakcejeva (2012) to extend the shelf life of cranberry fruits and reduce their moisture content. Since their skin is relatively thick, cranberries have to be dried for several to several dozen hours, which may have a negative effect on the content of bioactive components (Pokorný and Schmidt, 2003). Hot air drying significantly reduces drying time due to the increase in drying temperature (up to several dozen degrees). Apart from the drying air temperature, dehydration and exposure to oxygen also contribute to the degradation of bioactive compounds (Kalt, McDonald, & Donner, 2000; Pokorný and Schmidt, 2003; Stojanovic & Silva, 2007). Zielinska and Michalska (2016) dried berry fruits with hot air at a temperature of 60 and 90 °C and found that a lower drying air temperature and prolonged exposure to oxygen resulted in greater degradation of polyphenols and reduced antioxidant capacity. However, texture deterioration was observed when the convective heat transfer coefficient increased with an increase in the drying air temperature. Due to certain limitations of HACD, cranberries are often dried using a hybrid technology combining pretreatment and convective drying. Different

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pretreatments and osmotic dehydration combined with convective drying in a fluidized, pulso-fluidized and vibro-fluidized bed were used by Grabowski et al. (2007) for cranberry preservation. Other cranberry drying methods involve the use of microwaves. Microwave-vacuum drying (MWVD) was used for the dehydration of mechanically and osmotically pretreated cranberries (Sunjka, Rennie, Beaudry, & Raghavan, 2004). Wray and Ramaswamy (2015) used a microwave–vacuum dryer for the dehydration of fresh (frozen–thawed) cranberry fruits. Leusink, Kitts, Yaghmaee, and Durance (2010) compared the influence of microwave-vacuum drying and hot air-drying on the physical properties (moisture sorption isotherms, total porosity and pore size distribution) of cranberries. However, very few studies have compared the thermophysical properties of raw vs. HACD and MWVD cranberry fruits, which prompted us to undertake a study in this area.

The parameters of thermal processes such as drying, heating, freezing and refrigerating are selected based on the thermal properties of foods. The information about thermal properties is needed to design equipment for the above processes and adequately store food products. Knowledge about the thermal properties of food products is also necessary to perform heat transfer calculations. The thermal properties of foods are determined by their temperature, structure and chemical composition (water, protein, carbohydrate, fat, fibre, ash content). Choi and Okos (1986) developed equations for predicting the thermal properties of food components as a function of temperature. Numerous models have been proposed for estimating the thermal properties of foods based on composition data alone (Carson, 2006; Wang, Carson, North, & Cleland, 2008). Carson (2015) demonstrated that the thermal conductivity of particulate foods should range between 0.03 and 0.30 W m^{-1} K^{-1} when the porosity of material is greater than 25%. The thermal properties of food products can be determined using different methods and techniques. Thermal parameters can be determined directly with the use of measuring devices or indirectly based on mathematical calculations (Sahin & Sumnu, 2006). The KD2 Pro is a rapid and accurate thermal properties analyser for measuring the thermal conductivity, specific heat, thermal resistivity and thermal diffusivity of raw and convection microwave-dried vegetables (Chen et al., 2013; Perussello, Kumar, de Castilhos, & Karim, 2014, 2015) and fruits (Barnwal, Singh, Sharma, Choudhary, & Saxena, 2015; Kadam, Kaushik, & Kumar, 2012).

The aim of this study was to compare the thermal properties (thermal conductivity, specific heat and thermal diffusivity) of dried cranberries measured with a thermal probe with the values calculated based on their chemical composition. Cranberries were dried by hot air convective drying (HACD) and microwave vacuum drying (MWVD), and the influence of the drying method on selected thermophysical properties of fruits was also evaluated. Changes in the texture and physicochemical properties of cranberries, observed on the surface of and inside dried fruits, were described with the use of microstructure and macrostructure images.

2. Materials and methods

2.1. Materials

Fresh cranberries (*Vaccinium macrocarpon L.,* cv. Pilgrim) were obtained from a local farm (Klementowice, Poland). Whole cranberries were packed in sealed plastic containers several hours after harvest. Ripe fruits were free from any diseases, and were comparable in terms of freshness and size. The fruits were refrigerated (2 ± 2 °C, relative humidity of 90%) for up to two weeks. Refrigerated berries were warmed at room temperature for 2 h to reach the same equilibrium temperature before drying experiments.

2.2. Drying methods

Cranberries were subjected to hot air convective (HACD) and microwave vacuum (MWVD) drying. The weight of fruits used in each drying experiment was 0.200 ± 0.003 kg. HACD was conducted in an oven at 80 °C (FED53 127 Binder, USA). A single layer of fruits was spread uniformly on a mesh tray suspended from a digital balance accurate to 0.001 g (RADWAG, WPS 4000/C/2, Radom, Poland) and mounted on the top of the drying chamber. Mass losses during drying were monitored, and the drying process was stopped when no changes in sample mass were recorded over a period of 5 min (Sharma & Prasad, 2004). During HACD, a J-type thermocouple (Czaki Thermo, Raszyn-Rybie, Poland) with ±1 °C resolution was used to measure the temperature of the dried material. The tip of the thermocouple was positioned near the geometric centre of the fruit. The MWVD process was conducted in a microwave-vacuum chamber (Promis Tech, Wroclaw, Poland) where microwave power density and absolute pressure were 0.75 W g^{-1} and 4–6 kPa, respectively. The drying container rotated at 6 rpm. The MWVD system has been described in detail elsewhere (Zielinska, Zapotoczny, Alves-Filho, Eikevik, & Błaszczak, 2013). Successive portions of raw material were subjected to increasing drying times to measure the loss of mass (Figiel, 2009). As in the case of HACD, mass losses were monitored during MWVD and the drying process was stopped when the temperature of the dried material increased suddenly and no changes in sample mass were observed over a period of 1 min. The drying chamber was equipped with a pyrometer to measure the temperature of the dried material. The drying experiments were conducted in triplicate.

2.3. Analyses of the physical properties of cranberry fruits

Apparent density and substance density were determined to calculate the apparent porosity of cranberries. Following Rahman (1995), apparent density was defined as the density of a substance including all pores remaining in the material (ρ_{ap}), whereas substance density (ρ_s) was defined as the density of a substance that has been thoroughly broken into pieces small enough to guarantee that no pores remain. In the present study, substance density was determined with a pycnometer by direct measurement of the volume of liquid displaced (Odeniyi, Onu, & Adetunji, 2011). A glass pycnometer with a capacity of 100 cm^3 (LG-3838-3658, Chemland Ltd., Poland) and toluene, a water-insoluble liquid, were used in the experiment (Vilche, Gelycheck, & Santalla, 2003). Apparent density was determined based on the chemical composition of the sample and by the buoyancy method. The buoyant force was determined from sample weight in air and liquid (Rahman, 1995). The measurements were conducted in triplicate. Apparent porosity was defined as the ratio of total enclosed air space or void volume to the total volume of a material (Rahman, 1995). It was calculated based on the values of apparent density and substance density, from the following formula (1) (Rahman, 1995):

$$\varepsilon_{ap} = 1 - \frac{\rho_{ap}}{\rho_s} \quad (1)$$

where: ε_{ap} - apparent porosity, ρ_{ap} - apparent density, ρ_s - substance density.

The volume of cranberry fruits was determined based on the measured values of mass and apparent density of fruits (Joardder, Kumar, Brown, & Karim, 2015). Shrinkage was calculated as the ratio (converted to percentage) of the volume of dried fruits to the