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Heat and mass transfer enhancement during foam-mat drying process of lime juice: Impact of convective hot air temperature

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ABSTRACT

Foam-mat drying has been recently welcomed as an effective technique since it lacks deficiencies that plague conventional methods including poor water absorption and long process time. In this study, effect of hot air temperature (50, 60 and 70 °C) on quality properties of lime juice was investigated during foam-mat drying. The process was also simulated to determine the effect of temperature on the uniformity of moisture and temperature distributions during drying. Increase in temperature improved powder flowability. With a decrease in temperature, water absorption index increased by 17.74%. Moreover, effective moisture diffusion coefficient increased as a result of a rise in temperature, which, in turn, increased the drying rate by 20.23%. Increase in temperature also resulted in a 1.80% increase in the total color change and 6.60%, 1.18% and 1.35% decrease in chroma index, hue angle and browning index, respectively. A correlation coefficient of 0.903 was achieved between experimental and simulated data. Uniform distributions of temperature and moisture during drying resulted in an improvement in the qualitative properties of the final product regarding the uniformity of the powder's moisture content, improvement of water absorption properties and, finally, increase in the product's quality.

1. Introduction

Lime (*Citrus latifolia*) is from the citrus genus with growing global use [1]. Its production is limited to a select number of countries and specific areas due to the genus' sensitivity to low temperatures [2]. It can be planted in countries with hot and dry climates such as the USA, Argentina, Spain, Italy and Japan. The fruit can be used fresh, or as juice, concentrate, frozen or dried. It can be also used as powder in lemonade and sugar-containing drinks, candies and medicinal products. The main constituent of the fruit is water (88%) and its total soluble solids (TSS) include organic acids whereas sucrose (9.8%), protein (1%), ash (0.4%), food fiber ($< 0.1\%$), and citric acid (0.69%) make up the rest of its chemical compounds [1]. Lime is a rich source of nutrients such as flavonoids, citric acid, vitamin C, and minerals (like potassium) [2].

Raw fruits and vegetables have high water activity and are highly perishable against mechanical and microbial damages and ambient conditions. Water is one of the main constituents of food products that can affect fat oxidation, microbial growth, flavor and texture of dried products. Foods left in an open space start to exchange moisture with their surroundings to maintain their moisture equilibrium. Drying is the most common method to improve food durability as it curbs water and microbial activities and minimizes physical and chemical changes [3]. Hot-air (HA) drying is a simple prevalent technique for drying fruits and vegetables, but it is rife with disadvantages such as low energy efficiency and long process time due to low thermal conductivity of foods [4]. In HA drying, about two third of the process time is spent to remove the last one third of the moisture content. This is accompanied with quality degradation including discoloration, which can render the product unacceptable by the consumer [3]. Any improvement in the drying process without damaging the quality of the end product is thus specifically important [5]. Market requirements for high quality dried products have led to production of products with nutritional and organoleptic properties similar to those of fresh products. Additionally, new eco-friendly, energy-efficient, low-cost and safe drying technologies with better quality control capabilities are required [4].

Food powders are used to prepare products such as drinks, baked and dough products, snacks and baby foods. It is hard to dry juices and pulps of fruits with high sugar content due to the low molecular weight of sugars. Food powders can be produced by spraying juices into a spray dryer using food carriers. However, it is essential to apply simple alternatives for removing moisture from heat-sensitive foods with high

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sugar content and viscosity [6]. Foam-mat drying (FMD) was developed in the early 60s [7]. FMD is the simplest drying method compared to other techniques such as freeze-drying and spray-drying. It is inexpensive and less-complicated and takes less time for processing [8]. Foam-mat drying has been recently welcomed as an effective technique since it lacks deficiencies that plague conventional methods including poor water absorption, unsatisfactory sensory properties, and long process time [9]. The powder from this method has a brighter color, and its packaging leads to substantial product stability [8]. An FMD objective is to develop a stable foam structure to increase the drying rate and help scrape off the product from the tray [10]. This method has been tested for cowpea, apricot puree, banana, mango, apple sauce, tomato juice and paste, shrimp, etc. [9].

Flavor, color and water holding capacity of fruit powders have turned them into a good choice for instant juices, snacks, cakes, sauces, and baby foods [11]. Parameters such as temperature, air velocity, and relative humidity of the drying air, foam layer thickness and its composition can affect the quality of the final product including physicochemical characteristics, moisture content, bulk density, absolute density, interparticle porosity and solubility, which play a substantial role in final powder stability and its rehydration capacity [10]. Moisture content, bulk density, interparticle porosity, wettability and solubility of food powders are central to controlling quality during storage and also affect rehydration capacity. Moreover, powder color, as an important sensory characteristic, is a function of drying parameters (temperature and air velocity) as well as the kind of drying process [6]. Flavor compounds can have physicochemical reactions with substances within the food matrix and play an important role in maintaining volatile compounds. Polysaccharides and proteins with high molecular weight, compared to low-weight carbohydrates, can trigger the falling-rate period of the drying earlier. As the constant-rate drying period shortens, less aromatic compounds are removed by diffusion [9,12].

Raharitsifa et al. [13] studied the effect of foaming agent and stabilizer on FMD of apple juice. Egg white as the foaming agent (0.5, 1, 2, and 3%) and methyl cellulose as the stabilizer (0.1, 0.2, 0.5, and 2%) were added to apple juice and were stirred for 3, 5 and 7 min before drying. The foam from egg white had a better structure with higher foaming capacity and finer bubbles, but its stability was lower than foams from methyl cellulose. Moreover, higher methyl cellulose or egg white concentrations improved stability. Stability increased as the stirring time was increased. Peak foam stability was recorded at 0.2% methyl cellulose and 2–3% egg white concentrations.

In another study, tomato juice was foam-mat-dried by using egg white as the foaming agent at concentrations of 0.5, 10, 15 and 20% [14]. The foamed juice with 2.5 mm thickness was spread on a tray and was HA dried at 60, 65 and 70 °C. Incorporation of 10% egg white during 5 min of stirring resulted into the most stable foam. Foams dried at 60 °C for 510 min and 70 °C for 450 min showed the best results. In the same study, tomato pulp was also dried using the FMD technique at 60 and 80 °C [14]. The foam was spread on aluminum trays with 2 mm foam thicknesses. Results showed that the stirring time had an important effect on foam density. Additionally, foam stability was largely affected by stirring time and albumin concentration. The best foaming conditions in terms of the highest stability included albumin concentration of 4.5% and stirring time of 4.5 min.

Papaya pulp was incorporated by methyl cellulose (0.25, 0.5, 0.75 and 1%) as the foaming agent in another study [15]. The resulting foam was dried in a non-continuous cabinet dryer at 60, 65 and 70 °C with 2, 4, 6, and 8 mm thicknesses. Results showed that the best combination in terms of foam stability and nutritional properties of the final powder occurred at 0.75% methyl cellulose concentration and stirring time of 15 min with a 4 mm thickness dried at 60 °C. The foam overrun was generally affected by pulp and methyl cellulose concentrations.

Heat and mass transfer were modeled in another study during forced-air drying of yacon roots with osmotic pretreatment [16]. Following initial preparation, yacon roots were cut cylindrically in 2 mm slices and were treated in an osmotic solution at 30 and 50 °C and at 0 and 4 m/s stirring velocities. Convective drying was carried out in a tray dryer with forced air for 3 h at 60 and 80 °C. Process was simulated in a 2D axisymmetric mode in COMSOL Multiphysics. The main objective of the simulation was to examine the model's consistency with thermophysical properties such as specific heat and thermal conductivity as a function of moisture. Model and experimental data demonstrated a high correlation (> 0.9).

Abbasi and Azizpour [17] investigated the effect of egg white and methyl cellulose on the density and volume of foam samples during the FMD of sour cherry concentrates. The methyl cellulose solution (1, 1.5 and 2 g per 100 g), egg white (1, 2, 3 g per 100 g) as foaming agent, and maltodextrin (8 g per 100 g) as stabilizer were added to the sour cherry concentrate. The mixture volume was increased to 120 ml by distilled water. Following stirring, 3 mm foam layers were spread on aluminum trays and were dried at 50, 65 and 80 °C in a cabinet dryer. The sour cherry powder was then obtained by passing it through a sieve. The powders treated at 65 °C had the highest solubility.

In general, drying is considered an energy-intensive process accounting for more than 15% of the total industrial energy consumption. In addition, food quality during the drying process is a controversial topic. Therefore, it is essential to gain a deeper insight about the drying physics using mathematical models that are used for understanding the physical mechanisms, optimizing energy consumption, and improving the final quality. It is also necessary to understand temperature and moisture distribution through the foam during the drying process because it determines the final product quality. Moisture distribution is the main contributing factor to evaporation because this process depends on the surface moisture content. The evaporation rate leaves an important effect on heat and moisture transfer as the drying rate increases at higher evaporation rates [18].

To the best of our knowledge, there is no investigation in the literature about the influence of different air temperatures on qualitative and quantitative indexes of foam-mat dried lime juice and also heat and mass transfer modeling during FMD of the product. Therefore, the aim of this study was to both experimentally and numerically investigate the effect of air temperature on performance of lime juice FMD.

2. Material and methods

2.1. Raw materials

Lime fruits (*Citrus latifolia*) were purchased from a local market and juiced up. The extract was filtered using a mesh (#18) and kept at 4 °C [1]. Ovalbumin powder (egg white) (Sigma-Aldrich, A5253-250G) was purchased and stored at 4 °C. Methyl cellulose powder (Sigma-Aldrich, M0512-100G) was also purchased to prepare a 5% solution and kept at room temperature [17]. To prepare methyl cellulose solution, 5 g of the methyl cellulose powder was slowly added to 100 ml of hot water (90 °C) under fast stirring (1200 rpm). After stirring the resulting cloudy solution for 45 min, it was gradually cooled down to 5 °C using ice. The partly transparent solution was kept for 24 h at 4 °C for dissolution and better transparency [17]. Toluene was used to measure the volume of lime juice powders using the displacement method [19].

2.2. Foaming method

Amounts of methyl cellulose and ovalbumin concentrations were obtained by trial and error. Primary experiments revealed that foam drainage was very high in the methyl cellulose concentrations of less than 1.5% and ovalbumin concentrations of below 2%. However, with a concentration of at least 2% for ovalbumin and 1.5% for methyl cellulose, foam stability was acceptable due to a lower drainage. To produce foams, methyl cellulose (1.5% w/v) and ovalbumin (2% w/v) were added to lime juice. The obtained mixture was stirred in a 1 L beaker for 3 min using an electric mixer (Moulinex, HM-615, 500W) at