

POROSITY, COLOR, TEXTURE, AND MICROSCOPIC STRUCTURE OF RUSSET POTATOES DRIED USING MICROWAVE VACUUM, HEATED AIR, AND FREEZE DRYING

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ABSTRACT. Microwave vacuum drying (MVD) provides an alternative drying method for making dried products with a puffed, porous texture. This article describes the porosity, color, texture, and microscopic analysis of potatoes dried using MVD, heated air (HAD), and freeze drying (FD). The porosity was calculated from a ratio of apparent density and true density. A mathematical model for calculating true density from moisture content and apparent density was derived. Potatoes dried using MVD had 20 times the porosity compared to HAD potatoes; but FD had the highest porosity. Puncture tests and SEM images supported indirect and direct confirmation for the experimental porosity. Texture measurements indicated that MVD potatoes were crispy and porous, HAD potatoes were hard and brittle, and FD potatoes were spongy and subject to shatter. MVD potatoes retained more fresh-like color compared to HAD and FD potatoes.

Keywords. Porosity, Dehydration, Microwave dryers, Potatoes, Heating.

Heated air drying (HAD) is commonly used to dry food products because it is economical, requires a relatively low capital investment. However, severe case hardening and shrinkage of the tissue of fruits and vegetables can occur, decreasing the overall quality of HAD treated foods, particularly for products that have to have a puffed texture or which need to rehydrate rapidly. With freeze drying (FD), it is possible to eliminate case hardening and preserve shape, since water removal occurs by sublimation. FD results in little or no shrinkage compared to HAD. However, FD requires more time leading to an expensive operation and one with a high capital investment. Microwave vacuum drying (MVD) has been investigated as an alternative drying method that can produce puffed dried products (Lin et al., 1998; Drouzas et al., 1999; Yousif et al., 1999; Sham et al., 2001, Durance and Wang., 2002; Clary et al., 2007) at potentially lower cost than FD.

MVD often leads to reduced shrinkage and provides dehydrated foods with expanded porous cellular structure developed in vacuum (Drouzas et al., 1999) under internal vapor pressure generated by microwave heating (Feng et al., 2001). The porous structure of MVD products often results in shorter rehydration time (Durance and Wang., 2002; Giri and

Prasad, 2007), more complete rehydration (Giri and Prasad, 2007) and higher water retention (Lin et al., 1998). Drying foods with a relatively low initial moisture content at a high microwave power yielded dehydrated products with a low density and optimal puffing (Feng and Tang, 1998; Krulis et al., 2005; Kim and Bhowmik, 1997). Kim and Bhowmik (1997) also observed that shrinkage of dehydrated yogurt increased linearly in relation to moisture content, while bulk density did not.

Krokida and Maroulis (2001) measured the porosity of dehydrated and rehydrated potato, apple, banana, and carrot produced by different dehydration methods including HAD, FD, vacuum drying, and microwave drying. The porosity (ϵ) can be calculated from the apparent density (ρ_b) and true density (ρ_p) as:

$$\epsilon = 1 - \frac{\rho_b}{\rho_p} \quad (1)$$

Apparent density is defined as the ratio of mass versus the volume within the surface profiles of individual particles, it is also referred to as particle density. Bulk density is defined as the ratio of mass versus the volume occupied by the bulk materials including air voids between particles. True particle density is defined as the ratio of mass versus volume occupied by the solid and liquid materials within individual particles.

MVD products have a lower apparent density than HAD products, often half as much. The same foods treated by FD have the lowest apparent density (Lin et al., 1998; Sham et al., 2001; Durance and Wang, 2002). Sham et al. (2001) observed puffing in drying apple chips dehydrated with MVD at 28 mmHg (3.8 kPa) through the formation of a honeycomb network structure composed of closely interconnected cells. MVD also required less heat compared to HAD leading to less shrinkage and stretching of cell layers in the epidermis and palisade layers of sweet basil (Yousif et al., 1999).

Krokida and Maroulis (2001) indicated that different drying methods had no influence on the true density of food

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materials for a given moisture content. These researchers also provided empirical data for true density of potato, apple, banana, and carrot and from these derived a mathematical model to predict the true density of potatoes at different moisture contents.

The objective of this research was to study the porosity properties of MVD, HAD, and FD Russet potato slices and to evaluate color, texture, and microscopic structure of the dehydrated products. True densities of dried potatoes were determined.

MATERIALS AND METHODS

SAMPLE PREPARATION

Russet potatoes (*Solanum tuberosum*) were peeled, washed, and cut into cylinders (3.5 cm dia.) and sliced to 3-mm thickness before blanching in 98°C tap water for 2 min. The blanched potato slices were cooled in ice water for 2 min and then drained on paper towels to remove excess water. The samples were dehydrated with one of the three different drying methods described as following:

Microwave Vacuum Dehydration (MVD)

Drying system (MIVAC®, Boeing, St. Louis, Mo.) was described by Clary et al. (2005) with modifications (Setiady et al., 2007). The drying was conducted at a product surface temperature of 60°C, drying time 150 min, and initial microwave forward power at 1-W/g fresh potatoes, using a rotating turntable at 5 RPM, and a vacuum of 2.27 kPa. A MVD method with continuous temperature control described by Clary et al. (2005, 2007) and modified by Setiady et al. (2007) was used. This MVD system has the ability to control the application of microwave power by using an infrared detector to measure surface temperature of the product during dehydration. Product surface temperature during drying was controlled at 60°C since previous experiments indicated that drying at this temperature produced dried potatoes with more desirable functional characteristics than drying at either a higher or lower temperature (Setiady et al., 2007).

Heated Air Drying (HAD)

A 3-kW Dryer, Model UOP 8 (Armfield Technical Education Co. Ltd., Ringwood, Hampshire, England) was used at 60°C for 360 min and 1.8-m/s air velocity,

Freeze Drying (FD)

A Freeze Mobile 24 and Unitop 600L (The Virtis Co., Gardiner, N.Y.) was used at 0.013 kPa with a chamber temperature of 22°C and condenser temperature of -55°C.

ANALYTICAL METHODS

Moisture Analysis

Moisture content of fresh and dried potatoes was determined using AOAC method 44-15A (AOAC, 2000).

Apparent Density Analysis

Total volume occupied by dried individual potato pieces was determined according to Krokida and Maroulis (2001) by measuring the volume displacement of the potato samples

in *n*-heptane (ca. ± 0.5 mL). The apparent density was calculated by dividing the mass of the potatoes samples by the measured volume.

Mathematical Models for True Density

True particle density (ρ_p) is mass of solid (m_s) plus mass of water content (m_w) divided by the volume of the solid (v_s) plus the volume of water (v_w) or

$$\rho_p = \frac{m_w + m_s}{v_w + v_s} \quad (2)$$

$v_s + v_w = v_p$, with v_p for true volume. Equation 2 can be rewritten using the density of water (ρ_w) and density solid (ρ_s) as:

$$\rho_p = \rho_w \frac{v_w}{v_p} + \rho_s \frac{v_s}{v_p} \quad (3)$$

$$\rho_p = \rho_w \frac{v_w}{v_p} + \rho_s \left(1 - \frac{v_w}{v_p}\right) \quad (4)$$

Moisture content (wb) (MC_{wb}) is the mass of moisture or water (m_w) divided by the total mass, which is the mass of solid (m_s), water (m_w), and air (m_a). The mass of air is set to zero.

$$MC_{wb} = \frac{m_w}{m_p} = \frac{\rho_w v_w}{\rho_p v_p} \quad (5)$$

Substituting v_w/v_p in equation 4 with modifications as per equation 5, will lead to

$$\rho_p = MC_{wb} \rho_p + \rho_s \left(1 - MC_{wb} \frac{\rho_p}{\rho_w}\right) \quad (6)$$

$$\rho_p = MC_{wb} \rho_p + \rho_s - \rho_s MC_{wb} \frac{\rho_p}{\rho_w} \quad (7)$$

$$\rho_p = \rho_s + MC_{wb} \rho_p \left(1 - \frac{\rho_s}{\rho_w}\right) \quad (8)$$

$$\rho_s = \rho_p - MC_{wb} \rho_p \left(1 - \frac{\rho_s}{\rho_w}\right) \quad (9)$$

$$\rho_s = \rho_p \left[1 - MC_{wb} \left(1 - \frac{\rho_s}{\rho_w}\right)\right] \quad (10)$$

$$\rho_p = \frac{\rho_s}{1 - MC_{wb} \left(1 - \frac{\rho_s}{\rho_w}\right)} \quad (11)$$

As a simple check of this mathematical model, when MC_{wb} of a product is 0 kg kg_{wb}^{-1} , $\rho_p = \rho_s$, and when MC_{wb} of a product is 1 kg kg_{wb}^{-1} (MC_{wb} of water), $\rho_p = \rho_w = 1 \text{ kg L}^{-1}$. Equation 11 was used to calculated true density of dehydrated potato pieces.

Color Analysis

Instrumental color of the fresh and dried potatoes was measured using a Minolta CM-2002 spectrophotometer (Minolta Camera Co., LTD, Chuo-Ku, Osaka, Japan) with an 11-mm measurement aperture. The CIE-Lab L^* , a^* , and b^* values were recorded. L^* , a^* , and b^* values indicate lightness, redness(+)/(-)greenness, and yellowness(+)/(-)blueness, respectively. Total color differential (ΔE) was also calculated, as follows:

$$\Delta E = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2}$$

Texture Analysis

Dried potatoes (N = 20) for each treatment were analyzed by a puncture test using a TA-XT2 Texture Analyzer (Stable Micro Systems, Godalming, Surrey, UK). A slice of dried potatoes was punctured with a 5-mm diameter round tip cylindrical probe at a travelling speed of 1 mm/s. Slices were positioned on the middle of a heavy duty plate (model HDP/90 Stable Micro Systems, Godalming, Surrey, UK) with an insert plate (9.5-mm dia hole) and the force that it took to fracture or shatter the potato was recorded. Force and work were obtained from the force-time curves. Force was determined from the height of the peak and work was from the area under the force-time curves.

Scanning Electron Microscopy Examination

Dried potatoes were cut and mounted on aluminum stubs and gold coated. All samples from different drying methods were examined and photographed with an SEM Hitachi S-570 camera (Hitachi Ltd., Tokyo, Japan) using an accelerating voltage of 20 KV. Micrographs were taken at a magnification of 70X for longitudinal sections and 200X for transverse sections.

STATISTICAL ANALYSIS

Data were analyzed by SAS 9.1 (System for Windows 2002-2003, Cary, N.C.), using analysis of variance and Fisher's least significant difference (LSD) procedure. Significance was determined at $P < 0.05$. All determinations were made at least in duplicate and all were averaged.

RESULTS AND DISCUSSION

POROSITY PROPERTIES AND MOISTURE OF DRIED POTATOES

In order to obtain a reliable value for solid density (corresponding to dry mass) of potato (ρ_s) to be used in equation 11, the experimental data for true density of potato reported by Krokida and Maroulis (2001) are shown in figure 1. From these, and extrapolating to 0% moisture content using a regression model ($r^2 = 0.995$), the solid density of potato ρ_s was determined to be 1.6 kg/L.

The moisture dependent true densities of dehydrated potato obtained from mathematical calculations according to equation 11 are in figure 1 plotted against moisture content (wb) with the solid density (ρ_s) set at 1.6 kg L⁻¹ and the density of water (ρ_w) as 1 kg L⁻¹. The true densities of MVD, HAD, and FD dehydrated potatoes were 1.53, 1.56, and 1.58 kg L⁻¹, respectively. These values are compared in table 1 based on models proposed in the Krokida and Maroulis (2001). It is clear from figure 1 that the higher than realistic values (1.90-1.97 kg/L) from Krokida and Maroulis equations (table 1) were caused by errors of extrapolation to low moisture contents.

The apparent density of MVD potatoes was significantly lower than HAD potatoes, FD potatoes had the lowest density due to the porous structure (table 2). This finding was similar to previous finding of Lin et al. (1998), Sham et al. (2001), and Durance and Wang (2002). The porosity of MVD potatoes was about 20 times that of HAD potatoes, while the porosity of FD was even higher than MVD. Krokida and Maroulis (2001) indicated that drying methods had no influence on true density, but moisture content influenced the

Table 1. Moisture content (kg kg_{db}⁻¹ and kg kg_{wb}⁻¹) (n = 15) and different true density (kg L⁻¹) values based on Krokida (ρ_p (K)), modifications from Krokida (ρ_p (MK)), and mathematically calculated (ρ_p (MC)) as equation 11.

Sample	MC (kg kg _{db} ⁻¹)	MC (kg kg _{wb} ⁻¹) ^[a]	ρ_p (K) (kg L ⁻¹)	ρ_p (MK) (kg L ⁻¹)	ρ_p (MC) (kg L ⁻¹)
MVD	0.077 ± 0.007 ^c	0.072 ± 0.006 ^c	1.90	1.58	1.53
HAD	0.049 ± 0.004 ^b	0.046 ± 0.003 ^b	1.94	1.59	1.56
FD	0.025 ± 0.006 ^a	0.025 ± 0.006 ^a	1.97	1.60	1.58

[a] a-c Means in a column with different superscripts are significantly different ($\rho < 0.05$).

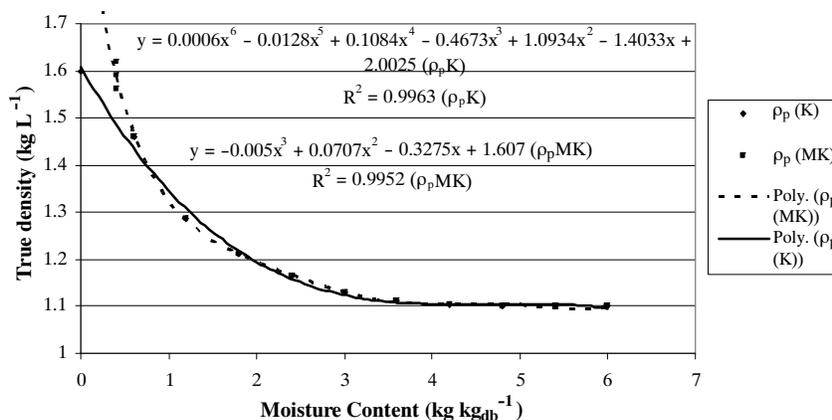


Figure 1. True density (kg L⁻¹) derived from Krokida (ρ_p (K)) and modifications to Krokida (ρ_p (MK)) at various moisture contents (kg kg_{db}⁻¹) from (Krokida and Maroulis, 2001).

Table 2. Apparent density (ρ_b (kg L⁻¹)), true density (ρ_p (kg L⁻¹)), and porosity (ϵ) values of MVD, HAD, and FD potatoes.

Sample	ρ_b (kg L ⁻¹) ^[a]	ρ_p (kg L ⁻¹)	ϵ
MVD	0.93 ± 0.11 ^b	1.53	0.39
HAD	1.53 ± 0.11 ^c	1.56	0.02
FD	0.52 ± 0.04 ^a	1.58	0.67

[a] Means in a column with different superscripts are significantly different ($p < 0.05$).

true density of the products. Sample porosity would probably provide a better overall indication of the product structure.

COLOR AND TEXTURE OF DEHYDRATED POTATOES

HAD processing led to significantly darker potatoes compared to the other drying treatments tested here. FD potatoes had the lightest color (table 3). MVD potatoes were slightly lighter than the fresh-blanching potatoes. Dehydration significantly increased the redness of dried potatoes compared to the fresh-blanching control, including FD processing. HAD potatoes were significantly redder compared to MVD potatoes due to longer drying time, even though HAD and MVD potatoes dried at the same temperature (60°C). The yellowness of the dehydrated potatoes increased significantly during drying. Spectroscopic data and visual observations indicate that MVD potatoes had color properties similar to blanched fresh potatoes; the ΔE for HAD and MVD potatoes from blanched were similar.

The amount of force and work to fracture potatoes samples was highly variable, FD potatoes required less force to fracture or shatter than MVD and then HAD potatoes (fig. 2). Indication of case hardening and brittleness would be reflected as a larger force to fracture FAD potato samples which often correlates with sensory attributes of crumbliness, fragileness, and sponginess. Statistically, there was no significant difference among the amount of work required to fracture MVD, HAD, and FD potatoes, but FD potatoes had a tendency to require less work to shatter. Visual observation indicated that FD potatoes had a structure similar to a dried sponge that could break easily, that the MVD potatoes retained a somewhat porous cell structure and many of the HAD pieces exhibited case hardening.

MICROSCOPIC STRUCTURE OF DRIED POTATOES

Figure 3 shows SEM images of dried potatoes from a planar cut, while figure 4 shows SEM images of dried

Table 3. CIE-lab values^[a] for blanched, MVD, HAD, and FD dried potatoes (n = 80).

Sample	L* ^[b]	a* ¹	b* ¹	ΔE
Blanched	58.6 ± 3.2 ^b	-2.40 ± 0.29 ^a	-0.87 ± 1.0 ^a	0
MVD	60.3 ± 3.3 ^c	-1.07 ± 0.14 ^c	6.76 ± 1.6 ^c	7.93
HAD	56.5 ± 2.5 ^a	-1.00 ± 0.15 ^d	4.86 ± 1.4 ^b	6.26
FD	81.7 ± 2.5 ^d	-1.19 ± 0.20 ^b	9.73 ± 1.3 ^d	25.5

[a] L*, lightness; a*, redness(+)/(-)greenness; b*, yellowness(+)/(-)blueness; ΔE , total color differential.

[b] Means in a column with different superscripts are significantly different ($p < 0.05$).

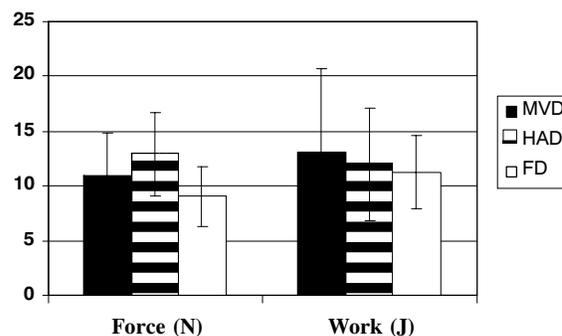


Figure 2. Puncture test results (force & work) for MVD, HAD, and FD dried potatoes (n = 20).

potatoes from a cross-sectional cut. The SEM image of MVD potatoes exhibit signs of cell expansion. Clary et al. (2007) indicated the puffed character of MVD grapes were distinct from that of sun-dried raisins. These SEM images show the effect of vacuum on creating a puffed characteristic in MVD potatoes (fig. 4).

During drying, cell walls collapsed in both MVD and HAD potatoes. However, because of the vacuum in MVD treatment, cell collapse was minimized. Hydrated starch could have formed enough of a continuous matrix to aid in the retention of air within the MVD potato. The SEM image of HAD potatoes showed the dense structure from cell wall collapse. HAD potatoes cell walls were compactly stacked on top of each other resulting in a rigid structure. The SEM image of FD potatoes indicated the rupture and fragility of cell walls from this drying treatment. The cross-sectional images of FD potatoes showed the tearing of cell walls from their base. This was consistent with the results of puncture analysis.

The SEM images show the different porosity of the dried potatoes. FD potatoes were the most porous and had minimal shrinkage, followed by MVD potatoes while HAD potatoes had the maximum shrinkage and were the least porous.

CONCLUSIONS

A mathematical model was derived to calculate potato true density based on moisture content and a known solid density of dried potatoes. MVD potatoes had the smallest true density and FD potatoes the highest true density. The porosity of MVD potatoes was 20 times that of HAD potatoes, while FD potatoes had even higher porosity. The results of the puncture test and interpretation of the SEM images suggest that MVD produced crispy porous potatoes, HAD harder and more brittle potatoes, and FD produced spongy and soft potatoes. MVD potatoes retained more fresh color compared to HAD and FD.

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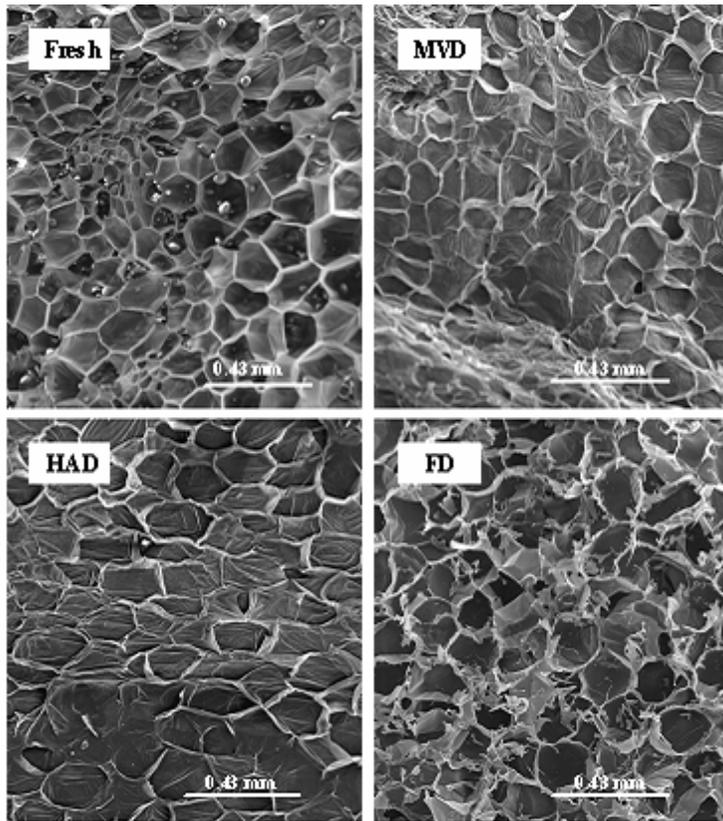


Figure 3. SEM (70×) images of fresh and dried MVD, HAD, and FD potatoes.

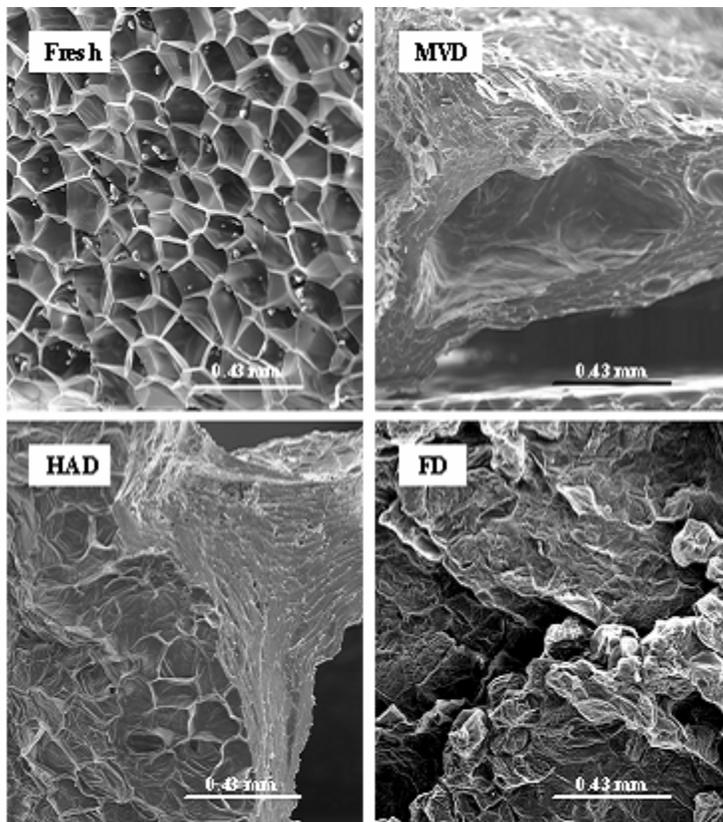


Figure 4. Cross-sectional SEM (70×) images of fresh and dried MVD, HAD, and FD potatoes.

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