DETERMINATION OF THE SHRINKAGE AND DENSITY OF THE FINAL PRODUCT AFTER CONVENTIONAL AND NONCONVENTIONAL DRYING

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ABSTRACT: The shrinkage and density of food during drying affect the quality of the dehydrated material. The deformation of pears during hot-air drying was greater than that during mid-infrared, vacuum and freeze-drying. The high material deformation during hot-air drying was due to the high temperature of the drying air and uneven heat distribution. Rapid drying rate conditions are used in infrared drying, which contributes to a relatively high shrinkage. There was a minimal difference between the infrared- and vacuum-dried samples, although the vacuum-dried samples were favored by low pressure. Less material deformation was observed during freeze-drying. The effect of vacuum and low drying temperature during freeze-drying generally leads to much less deformation. The product density changed similarly to the shrinkage. The following ranking was established based on the increase in density: freeze, vacuum, infrared, and hot air drying. In the case of the freeze-dried samples, we observed that the density changed by +4% compared to that of the raw sample.
KEYWORDS: material deformation, density, pear, drying 2 and 3D imaging

1. INTRODUCTION

The drying of biological materials, such as fruits and vegetables, typically involves high initial moisture content and invariably results in volume shrinkage [1]. This process is complex, encompassing simultaneous heat and mass transfer, which can lead to substantial alterations in the chemical composition, structure, and physical properties of food materials. The loss of water and the application of heat induce stress within the cellular structure of food, resulting in microstructural changes and shrinkage [2].

The movement of water from cellular locations to the surrounding environment causes irregular volume changes in high-moisture foods during drying, with this volume reduction commonly referred to as material shrinkage [3]. Empirical data from previous studies indicate that shrinkage is primarily a function of water content across a wide range of food products [4, 5].

The shrinkage of fruits and vegetables is occasionally described as material deformation. This phenomenon significantly impacts the mechanical and textural properties of these foods. Such shrinkage leads to volume reduction, alterations in shape and porosity, increased hardness, and surface cracking. It may also modify the microstructure and alter the heat and mass transfer and rehydration capabilities of the dried fruits [6]. From this perspective, shrinkage should be minimized, as this undesirable physical change may adversely affect consumer perception [7]. Consequently, the drying method and conditions employed have a substantial impact on product characteristics influenced by shrinkage and bulk density [8]. Bulk density may vary with the water content in the dried food product and is contingent upon the rate of shrinkage, which is significantly influenced by the drying method [9].

A variety of conventional and non-conventional drying technologies are currently utilized in the food industry for drying food materials. Conventional drying methods include hot-air, spray, solar, rotating drum, fluidized bed, and superheated steam drying. Non-conventional drying technologies, also referred to as gentle drying methods, encompass infrared, microwave, vacuum, freeze, and ultrasound drying [10].

Few studies have been conducted on changes in the density and shrinkage of pears after drying and the relationship between these two factors [11, 12].

The purpose of this study is to determine the degree of deformation of fruits preserved by various conventional and nonconventional drying methods (hot-air-, mid-infrared-, vacuum- and freeze drying) using a special digital microscope.

This is a new approach to determining the deformation of solid materials. In addition, examine whether there is a correlation between the deformation and density of the dried product by

different conventional and nonconventional drying methods.

2. MATERIAL AND METHODS

2.1. Material

The raw pear (*Pyrus communis* L.) employed in the experiments were purchased from the food store (Nyíregyháza, Hungary) and stored in a refrigerator (5°C). The pears were washed with tap water, hand-peeled and cored with a knife, and then cut into cubes of 10 mm thickness using a hand-operated slicer. The free water on the surface of samples was removed with an absorbent filler paper.

2.2. Drying methods

The pear cubes were dried by different drying methods with the optimal drying technology until the final moisture content (2-3%, wet basis: w.b.). The applied drying methods are described below-mentioned. The drying process was continued until a constant moisture content was recorded.

Hot-air drying (HAD)

Convective drying was carried out in a hot-air dryer (model LP306, LaborMIM, Hungary) at 80°C with an air flow rate of 1 m s^{-1}. Air humidity was regulated at 15-20%. The samples were spread uniformly, in single layer on the trays of dryer. The drying time of the experimental materials was 6 hours in the drying cabinet.

Mid-infrared drying (MIR)

A lab scale infrared dryer (model Precisa HA-60, Precisa Gravimetrics AG, Dietikon, Switzerland) was used, having with 2 quartz glass infrared emitter (a total of 410 W). The quartz glass emitter is located at a distance of 15 cm from the pear cubes surface. Infrared radiation, with wavelengths expressed in microns, can be accurately measured, controlled, and applied to the product. The wavelength of radiation between 2.4-3.0 µm and the heating intensity were maintained between 3-5.5 kW m^{-2} (Infrared intensity is usually expressed as radiation power per unit area). The following parameters were used for drying: temperature, 80°C; pressure, 1 bar; and drying time, 20 min.

Freeze drying (FD)

Freeze drying was performed in a laboratory-scale Armfield FT-33 freeze-dryer (Armfield Ltd., Ringwood, UK). In the FD process, the pear dices were spread uniformly in a single layer on a stainless steel tray. The pear samples were frozen at -24°C in a freezing/heating chamber and an absolute pressure of 50-90 Pa with a chamber temperature of 21°C and a condenser temperature of -33°C. In all experiments, temperature of the condenser and the chamber pressure were maintained at constant parameter. Thermocouples (four pieces) of freeze-dryer were inserted into the pear cubes. The drying time of the experimental materials was 22 hours.

Vacuum drying (VD)

The pear samples were dried in a vacuum (model Kambic VS-50C, Kambic Lab. Eq., Semic, Slovenia) at 80°C. The pressure in the vacuum dryer was 7 kPa during the drying process. The drying time of the experimental materials was 7 hours in the drying cabinet.

2.3. Determination of moisture content

The moisture content of the dried pear dices was determined using the gravimetric method (model LP306, LaborMIM, Hungary). 50-50 g of sample was used for each drying method. The samples were weighed using a digital balance (JKH-500, Jadever Co., Taiwan).

2.4. Digital microscope

Digital images of the dried material were captured from a particular direction using a digital microscope (model Keyence VHX-6000, Keyence Co., Osaka, Japan). Two- and three-dimensional images were sufficient to determine the degree of deformation (400×magnification). Digital imaging was performed on ten samples with triplicate replication. In each case, the microscope detected the greatest difference between the upper edge of the product and the recess of the product.

2.5. Determination of density: gas pycnometry

Gas pycnometer measurements were conducted using an Ultrapyc 5000 gas pycnometer (Anton Paar GmbH, Graz, Austria) with helium as the working gas. This method allows for the near-accurate determination of the true density of samples by measuring their volumes. Initially, a dried sample was placed in a primary container with a calibrated and precisely known volume at atmospheric pressure. Helium was then introduced into the container until a specific pressure, P1, was reached. Subsequently, the gas is expanded to a predetermined pressure, P2, in an adjacent empty expansion vessel, which has a known volume at atmospheric pressure. The pycnometer measures the volume of gas displaced from the primary container at pressure P1 to the expansion container at pressure P2. The change in pressure facilitated the determination of the sample volume.

The density of the solid sample was then calculated using the mass of the sample, which was measured with a balance prior to analysis, and the determined sample volume.

2.6. Statistical Analysis

The experiments were performed in triplicate (n=3). Data analyses were determined using the PASW Statistics 18 software (IBM Corp., Armonk, USA), and analyses of variance were conducted by ANOVA procedure, Duncan test. Mean values were considered to be significantly different when $P<0.05$.

3. RESULTS AND DISCUSSION

3.1. Analysis of the deformation of dried materials

Figures 1-4 show the two- and three-dimensional views of hot air-, mid-infrared-, freeze-, and vacuum-dried pears, respectively. The upper part contains the three-dimensional image with the base points and the connecting lines, and the bottom part of the picture is the two-dimensional image with the distances (in µm) indicating the degree of deformation.

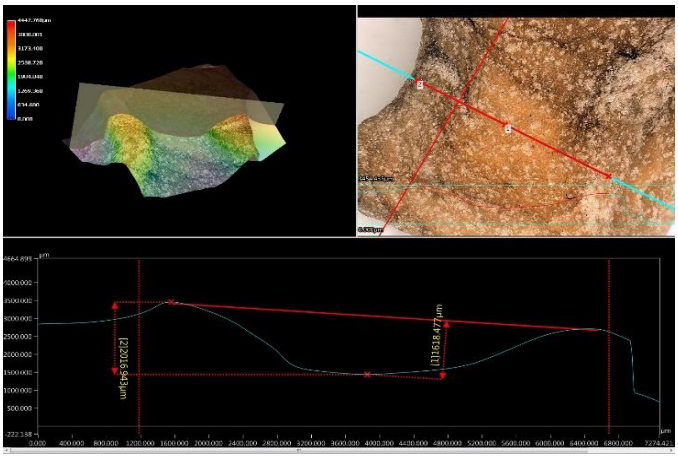

Figure 1. The 2 and 3D imaging of HAD dried material

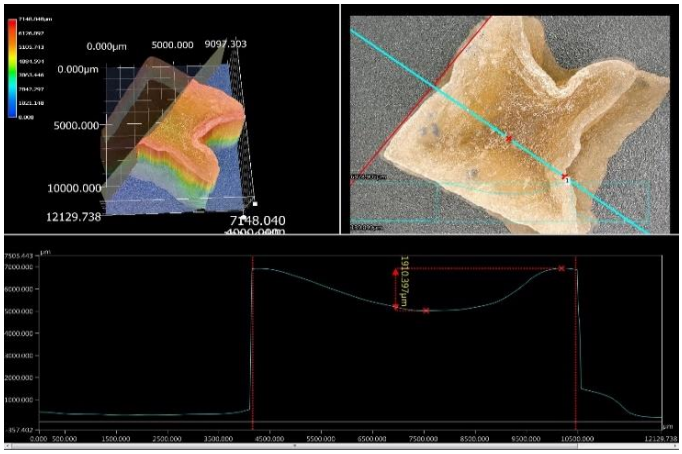

Figure 2. The 2 and 3D imaging of MIR dried material

The two-dimensional views shown in Figures 1 and 2 clearly show that the product dried using infrared drying (MIR) also shrank (1.91 mm), while the greatest deformation (2.01 mm) was observed in the hot-air drying method (HAD) due to the high drying temperature. However, there was a high shrinkage of pear samples dried by mid-infrared drying. This is because of the accelerated removal of water from the tissues in the sample by infra-wave [13]. Jiang et al. [14] showed that drying temperature significantly affected the volume reduction of carrot slices during hot-air drying. The higher the drying temperature in the early stages of drying and the greater the capillary pressure difference, the faster the rate of shrinkage of the carrot slices.

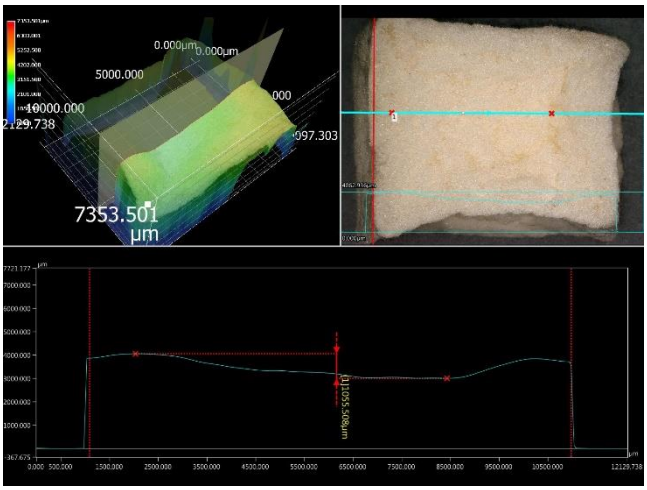

Figure 3. The 2 and 3D imaging of FD dried material

Similar to Ratti's results, minimal deformation (1.05 mm) was observed on the surface of the freeze-dried pears. Ratti found that the shrinkage during freeze-drying was minimal (5–15%), whereas during hot-air drying, it was excessive (approximately 80%) [15]. Krokida et al [16] found that the food raw material did not shrink significantly during freeze-drying at low temperatures (estimated glass transition temperature: below -45 °C) and under high vacuum.

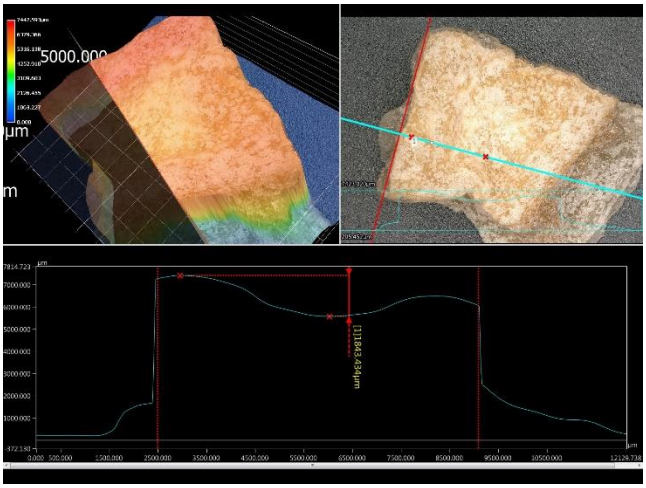

Figure 4. The 2 and 3D imaging of VD dried material

In the case of vacuum dried pear cubes, a slight deformation (1.84 mm) was observed.

Figures 1–4 illustrate that the freeze-dried product exhibited the least amount of damage, followed by the vacuum-dried and infrared-dried materials. In contrast, the hot-air drying method resulted in the most significant deformation.

Table 1 shows the degree of deformation caused by various drying methods.

Based on the smallest and largest product deformations, the following ranking was established: freeze-drying (FD), vacuum-drying (VD), mid-infrared drying (MIR), and hot-air drying (MIR). A significant difference ($p \leq 0.05$) was observed between FD, VD, and MIR, but no significant difference ($p > 0.05$) was observed between MIR and HAD.

Table 1. Deformation due to conventional and nonconventional dehydration

Drying methods	Distance between the base point and the recess, H [mm]$^{\times}$	Ranking
HAD: Hot-air drying	1.934 ± 0.098^{cd}	4
MIR: Mid-infrared drying	$1,878 \pm 0.055^{c}$	3
VD: Vacuum drying	1.764 ± 0.085^{b}	2
FD: Freeze drying	$1,044 \pm 0.039^{a}$	1

$^{\times}$Marked with red in Figures 1-4.

Data are expressed as the average ± standard deviation for three replicate.
Different lower case letters (a, b, c, d) denote significant differences ($p \leq 0.05$).

3.2. Analysis of the density of dried materials

During the drying process, an increase in the density of pear cubes is anticipated. This phenomenon is attributed not only to the loss of water but also to shrinkage, which significantly reduces the volume of the sample. Consequently, the resulting products exhibit a higher solid content per unit volume. Similarly, Gabas et al. [17] reported an increase in the bulk density of plums as the moisture content decreased. This phenomenon was attributed to the collapse of fruit cells, which resulted in a reduction of air pores within the fruits and, consequently, a decrease in the volume of the samples.

Table 2 shows the results of the density measurements of raw pear samples and those dried using different methods.

Table 2. The results of the density measurement

Drying methods	Density [g cm^{-3}]	Ranking
Raw samples	1.005 ± 0.04^{a}	-
HAD: Hot-air drying	1.461 ± 0.07^{c}	4
MIR: Mid-infrared drying	1.363 ± 0.05^{bc}	3
VD: Vacuum drying	1.267 ± 0.03^{b}	2
FD: Freeze drying	1.045 ± 0.04^{a}	1

Data are expressed as the average ± standard deviation for three replicate.
Different lower case letters (a, b, c) denote significant differences ($p \leq 0.05$).

Compared to the density of the raw, undried sample, the density of the freeze-dried product changed minimally, with no significant difference ($p > 0.05$) between them. There was a significant difference ($p \leq 0.05$) between the density of pear cubes dried using the other methods (HAD, VD, and MIR) and that of the raw material. There was no significant difference between ($p > 0.05$) the densities of the vacuum-dried and mid-infrared dried samples and those of the samples treated with the mid-infrared and hot-air methods.

Based on product density, the following ranking was established, from smallest to largest: freeze-drying (FD), vacuum drying (VD), mid-infrared drying (MIR), and hot-air drying (MIR). Freeze-dried pear cubes had the lowest density values among the other dried samples because this process allows ice to sublime, leaving voids within the structure without significant shrinkage [18]. The high density observed in the HAD patterns was due to the fact that hot-air drying caused significant shrinkage and collapse of the cell walls [19]. Baysal et al. [20] found that the bulk density and shrinkage values of garlic samples dried using infrared and hot-air methods did not show statistically significant differences.

4. CONCLUSIONS

The shrinkage and density of food during conventional and non-conventional drying significantly influence the quality of the dehydrated product. The deformation observed in pears subjected to hot-air drying was more pronounced than that observed in pears subjected to vacuum, mid-infrared, and freeze-drying methods. This substantial deformation during hot-air drying can be attributed to the elevated temperature of the drying air (80°C) and the uneven distribution of heat. In mid-infrared drying, the rapid drying rate conditions contribute to relatively high shrinkage. Although there was a minimal difference between the mid-infrared and vacuum-dried samples, the latter benefited from low pressure. Freeze-drying resulted in less material deformation, as the effects of vacuum (p=50-90 Pa) and low drying temperatures

(T=-24 to 21°C) generally led to significantly reduced deformation.

The results clearly show that the product density and shrinkage rate were strongly influenced by the drying process. A strong correlation was found between product deformation (shrinkage) and density, as the ranking established for the drying methods showed a similar pattern. This finding also affects consumer perceptions.

Further research is required to ascertain the efficacy of the digital imaging method in determining the deformation of dried products, such as the capability to measure shrinkage.

5. ACKNOWLEDGEMENTS

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